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4.5 Ion Implantation

- **Ion implantation is the process of directly injecting dopants into wafers.**
- **Ion implanters are classified in three categories: low/medium current, high current and high energy system.**

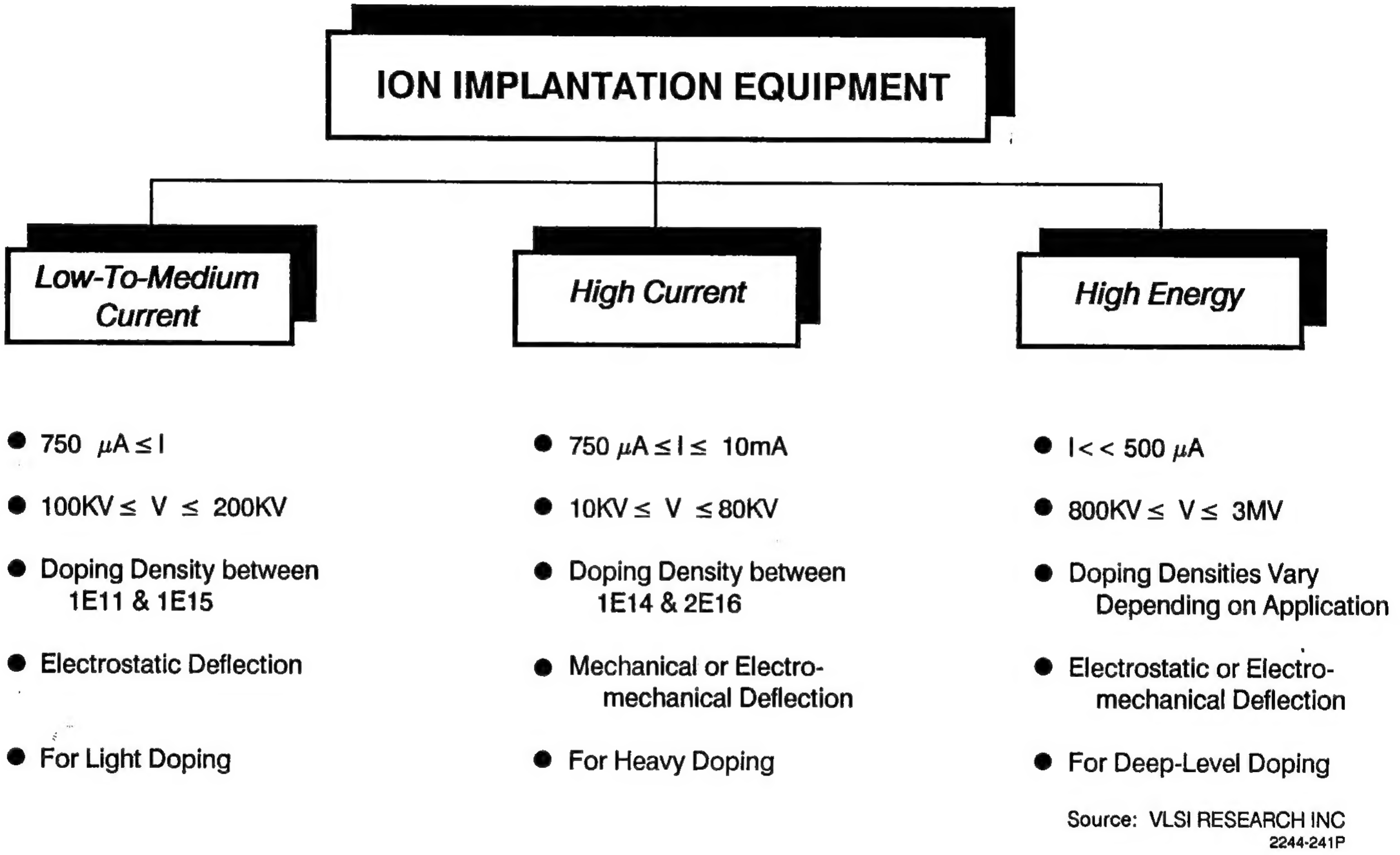
Ion implanters directly inject dopant atoms into semiconductor wafers. A gas containing atoms or molecules of the desired dopant 'species' is first ionized in an ion source. The ions are then extracted from the source and are accelerated through an electric field. This accelerating potential typically ranges from a low value of about 20,000 volts to more than 200,000 volts. The dopant ions thereby gain sufficient energy to penetrate the silicon surface and become embedded several atomic layers below the surface. Ion implanters were derived from their cousins, the 'linear accelerators', frequently used in atomic physics research, and are very similar in construction and operation.

Ion implantation equipment classification can be broken into three categories, as depicted in Figure 4.5.0-1, according to their ability to produce dopant ions with certain characteristics. These categories are low-to-medium-current machines, high-current machines and high energy machines. The first two are segregated according to the intensity of dopant ions the machine is capable of producing. The third segment, high energy, is distinguished from the others because implanters capable of producing high energy ion beams significantly differ in construction and are used for well defined applications.

Ion implantation equipment represented approximately 10% of the total wafer process equipment market in the late eighties. In 1989, for example, ion implantation equipment sales were approximately $471M. Section 4.5.9 gives more detailed data for current, past and future years.

Ion beam current is the term used to describe the number of dopant ions per second striking the surface of a wafer. One microampere of beam current is equivalent to 6×10^{12} dopant ions per second impinging on the wafer's surface. The practical significance of beam current is wafer *throughput*. Implanted dopant density is directly proportional to ion beam current. The lower the current, the lower will be the maximum wafer throughput capacity of the implanter for a given doping density. The total time needed to implant a single wafer is the sum of the time required to implant the total number of ions plus the time required to mechanically move the wafer into and out of the implant position. Early machines were limited to extremely low currents in the range of 5 to 25 microamperes. As machine technology improved, maximum beam currents achievable increased to the 400-to-750 microampere range. Using these higher beam currents, implant time decreased, and machine throughput (in wafers per hour) increased. These later genera-

Figure 4.5.0-1



- **ION IMPLANTATION EQUIPMENT**
  - ***Low-To-Medium Current***
    - $750\ \mu A \leq I$
    - $100KV \leq V \leq 200KV$
    - Doping Density between 1E11 & 1E15
    - Electrostatic Deflection
    - For Light Doping
  - ***High Current***
    - $750\ \mu A \leq I \leq 10mA$
    - $10KV \leq V \leq 80KV$
    - Doping Density between 1E14 & 2E16
    - Mechanical or Electro-mechanical Deflection
    - For Heavy Doping
  - ***High Energy***
    - $I << 500\ \mu A$
    - $800KV \leq V \leq 3MV$
    - Doping Densities Vary Depending on Application
    - Electrostatic or Electro-mechanical Deflection
    - For Deep-Level Doping

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tions of medium-current machines are also capable of performing low-current implants. Consequently, the market for low-current machines has gradually diminished. Low-to-medium-current machines are generally used for MOS threshold adjustments, and to produce wells for isolation. Bipolar processes routinely use ion implantation for fabrication of resistor and base regions.

High-current machine beam currents range from about 750 microamperes to more then 25 milliamperes. At one time it was assumed that high-current machines would displace the demand for medium-current machines, as happened with low-current systems. However, this has not happened because high-current machine designs used in high dose (heavy doping) applications are generally incompatible with low dose applications. Thus, two long term markets have evolved: the first centers on the low-to-medium-current applications, while the second centers on high-current applications.

The third category of ion implanters is the high energy machines. These systems have the ability to implant ions very deeply by accelerating ions to very high velocities. Most high-energy systems are only capable of beam currents of 5 to 50 microamperes but can produce ion energies well into the 2 to 3 MeV ranges. Uses for high-energy systems include deep wells in CMOS, three-dimensional interconnects, retrograde doping profiles and buried insulating layers of silicon dioxide (SIMOX) and silicon nitride.

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4.5.1 Current Industry Characteristics

- **Ion implantation offers three advantages: precise doping density control, uniform doping, and depth control.**
- **Ion implantation replaces diffusion deposition processes.**
- **CMOS devices would be nearly impossible to fabricate without ion implantation.**

Ion implantation offers three features that have outstanding advantages in semiconductor manufacturing. They are: a) precise control of impurity doping density, b) accurate control of the dopant depth distribution, and c) uniform deposition of dopants across the wafer surface.

Accurate control of impurity doping density is the most important and was the earliest application of the ion implantation process. Most VLSI circuits fabricated with MOS processes would be unattainable without ion implantation to adjust the threshold voltage of the MOSFET. Mostek was one of the first to ship MOSFETs using ion implantation in the early 70's.

Uniform wafer doping, coupled with accurate depth-distribution control, is perhaps next in importance. As early as 1974, Western Electric, Texas Instruments and others were using ion implantation to replace chemical pre-deposition. This process resulted in the ability to fabricate transistors with uniform gain (h_{fe}) across an entire wafer's surface.

Control of depth penetration has allowed device designers to accomplish a certain degree of tailoring of dopant profiles. This profile control results in the ability to tune device performance specifications which are not easily obtainable with diffusion techniques alone.

Both diffusion methods and ion implantation methods are used to selectively introduce impurity atoms into the wafer. When diffusion is used, it is usually accomplished in two steps. The first is known as the pre-deposition or 'pre-dep' step. The second step is called 'drive-in'. At pre-dep, the dopant atoms are deposited onto the wafer surface and allowed to diffuse to depths of only a few hundred angstroms. The temperature of the diffusion furnace for the pre-deposition step is set for achieving best control of the solid-solubility of the impurity (i.e.–maximum surface penetration of the dopant). At the drive-in step, the temperature is raised sufficiently high to permit the surface dopant to diffuse into the wafer within a reasonably short period. Drive-in processes typically use temperatures of 1000 to 1100 °C for periods of 60 to 90 minutes. These conditions result in diffusion depths in the range of one to two microns.

As ion implantation processes were perfected, they gradually replaced most pre-deposition processes and many shallow drive-in processes. Unlike the diffusion process, ion implantation is not an equilibrium phenomena that results for a fixed period of time when a wafer is held at a predetermined wafer temperature. Instead, ion implanters are used to achieve doping of wafers by bombarding or 'implanting' the wafer's surface with impurity atoms at near room temperature. However, the impurity atom profile or junction depth that is achievable with ion implanters is usually not sufficient for most transistor design. Moreover, the density of ions that could be produced in a reasonable time with early low current ion implanters could not reach the surface concentrations required. Both of these limitations had been somewhat mitigated with the newer generations of ion implanters. Also many of the latest generations of device structures use very shallow junctions that can be implanted directly.

As this market has evolved, only a few suppliers have been successful in producing viable production systems. Among these companies are Applied Materials, Eaton, Nissin High Voltage, Shinko Seiko, Varian and Veeco. Ion implanters are very complex machines, and have been plagued by poor reliability. Typical machine uptimes are not usually comparable with other types of wafer process equipment. End-users cite mechanical problems, especially with ion sources, end stations and vacuum systems as major causes of machine failure.

Ion implanters represent a large capital expenditure. In recession years it is commonly one of the first items to be cut from a semiconductor manufacturer's budget. A typical example of this situation occurred in 1986. Sales of ion implanters fell dramatically from the previous year. Device manufacturers found they had been under utilizing their installed implanter capacity, and concentrated their efforts on improving overall utilization of these large investments.

4.5.1.1 Development of the Industry

Initially, ion implantation processes were slow to be accepted. This resulted in slow growth in the equipment industry. The market probably would not have survived had it not been for the simultaneous emergence of MOS integrated circuits. Likewise, MOS integrated circuits would have had far less acceptance had it not been for the implantation process. Each technology assisted and enhanced the other. Even today, MOS integrated circuits are the only ones which *require* ion implantation in order to be produced economically at high volumes.

Ion implant equipment technology grew out of the technology developed for linear accelerators used in atomic research. Consequently, its history is closely linked to, and easily traced from, this endeavor. Several centers of linear accelerator activity have had significant impact upon the business. Primary among these were the United Kingdom Atomic Energy Research Establishment, Oak Ridge, and Stanford University. These government and university efforts spawned industrial implanter activities at Lintott Engineering Limited, Great Britain; High-Voltage Engineering Corporation, Massachusetts; Ortec, Tennessee; and Picker Nuclear in Austin, TX.

Many early research implanters were built internally while other researchers purchased and then modified systems. High Voltage Engineering Corporation, Lintott Engineering and Accelerators, Inc. delivered the very earliest ion implanters. These first systems were delivered in the late sixties and early seventies. The Lintott machines went to Signetics and Texas Instruments (Figure 4.5.1.1-1) while the High Voltage Engineering machine went to Fairchild. These machines remained in operation well into the eighties. Accelerators, Inc. of Austin, TX—formed by individuals from Picker Nuclear—sold its first systems to Texas Instruments (Figure 4.5.1.1-2 and Figure 4.5.1.1-3) and IBM in 1970. All of these machine designs were intended for laboratory research. They were very complicated and unwieldy and could not be easily used for routine production.

All implanter designs utilize subsystems that are basically similar. These basic building blocks are: 1) the ion source, 2) the accelerator, 3) the mass analyzer or separator, 4) the scanner, and 5) the target chamber or end station. These subsystems can be used in various configurations, as shown in Figure 4.5.1.1-4. Early implanter designs usually used a single acceleration stage and either used a magnetic analyzer or a device called an E cross B (ExB) filter (See a. and b. of Figure 4.5.1.1-4). The ExB filter design takes advantage of the fact that while the magnetic field separated the various ion masses by deflecting them, an electric field can be applied to oppose the magnetic deflection. The ions then travel in a straight line through the analyzer. The acceleration stage was usually placed before the analyzer. Since these early implanters were derivatives of atomic research tools that were mostly used to accelerate very light ions such as hydrogen and helium, the analyzers were usually very small with minimum resolving power. Heavier ions used in the implantation process required very large magnetic fields. These very large electromagnets—sometimes weighing as much as a ton—also consumed very large amounts of power and required large amounts of water cooling.

This led designers to 'split' the acceleration into two parts, pre-acceleration and post-acceleration, as shown in c. and d. of Figure 4.5.1.1-4. Pre-accelerators typically accelerate the ions to 15 or 20 keV. After mass analysis, the selected ions are again accelerated to their final energy, typically 80 to 200 keV. The split acceleration technique has the further advantage of accelerating only the required ion species to high energy. This further reduces power consumption and more importantly reduces the X-ray generation level resulting from removing the unwanted ions from the ion beam before acceleration.

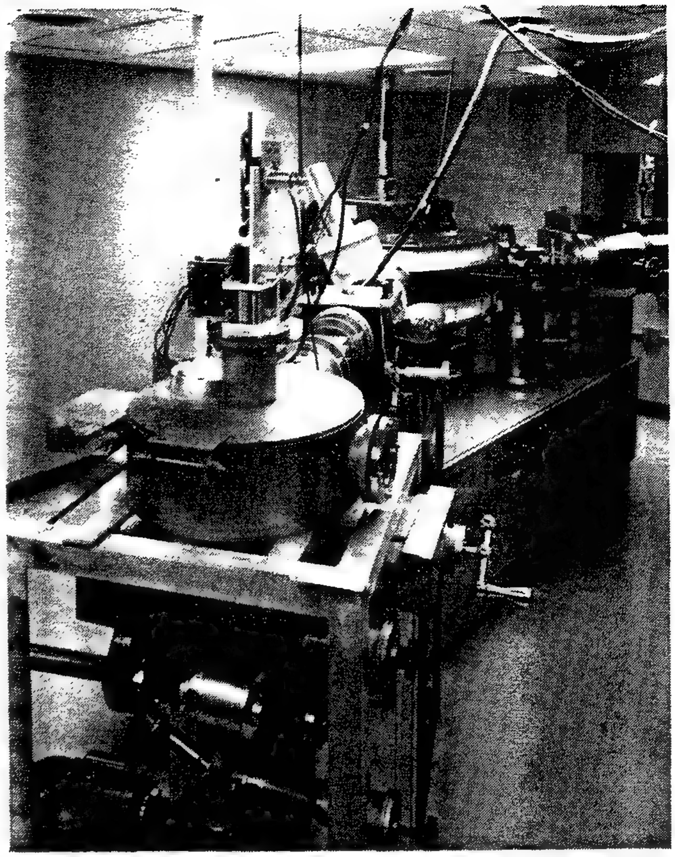

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Figure 4.5.1.1-1

Early Lintott Isotope Separator (circa 1969)

The majority of today's implanter designs are based on the concept shown in c. of Figure 4.5.1.1-4. This design optimizes the tradeoffs between power consumption, floor space and other technical and vacuum requirements. It also readily lends itself toeither electrostatic or hybrid scanning techniques. These tradeoffs will be discussed in a later section.

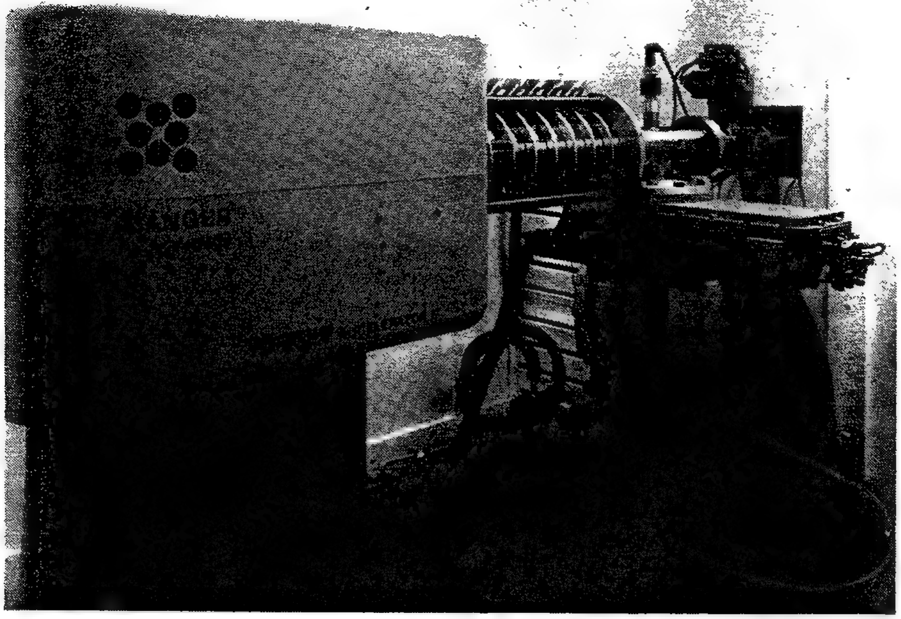

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Figure 4.5.1.1-2

One of the First Systems from Accel

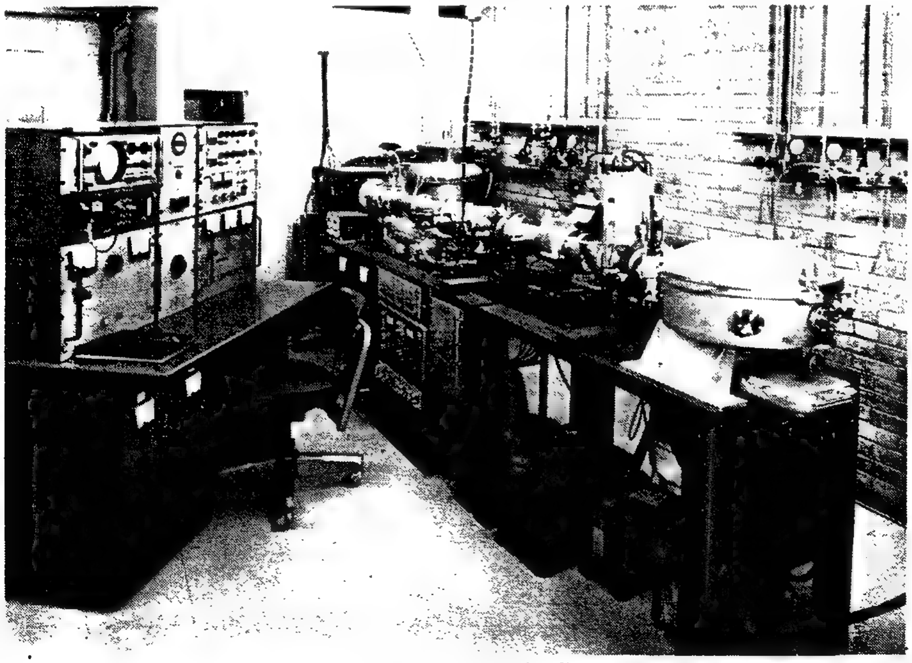

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Figure 4.5.1.1-3

Beam Scanner, End Station and Control Consol of 150keV Accelerators, Inc. Machine

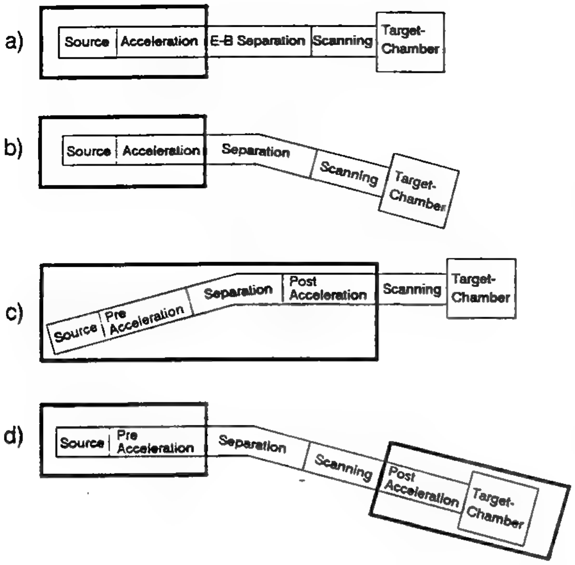

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Figure 4.5.1.1-4

Four Basic Implanter Configurations

Dr. Peter Rose and several colleagues who initially developed ion implanters at High Voltage Engineering left in the early seventies to form Extrion Corporation. By 1973, Extrion developed the first production implant machine. By the mid-seventies, Extrion had captured a commanding market share and required additional capital to fund expansion. Glouchester Engineering acquired Extrion in the mid seventies and subsequently sold the company to Varian. Varian-Extrion is one of today's leading implant equipment suppliers. Following the acquisition of Extrion by Varian in the late seventies, Peter Rose and several top Extrion managers left and founded Nova Corporation. Nova's initial market entry was a third generation machine aimed specifically at high current applications and it quickly captured the lead in that market segment. Nova was eventually acquired by Eaton, becoming that company's Ion Beam Division. Both Nova and Varian-Extrion are located near Boston.

Lintott Engineering continued supplying ion implant equipment until 1979. At that time, the ion implant portion of the business was sold to Applied Materials and subsequently renamed AIT (Applied Implant Technology). Simultaneously, the company was moved from Great Britain to Santa Clara, CA. The move proved unsuccessful and AIT moved back to Great Britain in 1983. It was then reconsolidated as a division of Applied Materials and has since done well. The company is well along the way to regaining the market share achieved early on by Lintott.

Accelerators, Inc. was acquired by Veeco in 1979. The Ion Implant Division at Kasper Instruments was another early spin-out founded by engineers from Accelerators, Inc. Kasper was subsequently acquired by Eaton and the Implant Division was merged with its Nova Group. The Eaton-Kasper Group is located in Austin, TX. Veeco left the market in 1987.

Ortec was founded by individuals from the Oak Ridge National Laboratory for the purpose of building nuclear instrumentation. Among the fruits of their efforts was an implant machine, introduced in the early 1970s. This machine was initially developed by Ortec for use internally to manufacture surface barrier particle detectors. The company's initial ion implanter product offering was a very compact low current machine designed primarily for MOS threshold adjustment processes. Only a few of these systems were shipped. Ortec didn't understand the rapidly changing semiconductor manufacturing industry and in 1973 sold its implanter to GCA. The group was moved from Oak Ridge to Sunnyvale, CA. At about the same time, GCA also acquired a small company in Walnut Creek, CA, that was founded by ion source experts from Lawrence Berkeley Laboratory. GCA attempted to redesign the Ortec machine to produce higher beam currents. This effort was largely unsuccessful and GCA left the market in 1981.

The market for low current implanters began declining in 1976. This was due to the emergence of modern medium current implanters. A medium current system has the capability to produce ion beam currents that span both the low and the medium current ranges. Low current implanters are no longer being built in the free world, though VLSI Research Inc received reports indicating some versions of low current systems were still being built in the Soviet Union and in China as recently as 1985.

Researchers realized very early that if the ion implantation process was going to compete economically with diffusion as a predeposition process, machines had to be capable of delivering large quantities of dopant atoms to the wafer in a short time. Machines, called isotope separators, capable of producing very large ion beams, were developed during the Second World War to produce enriched uranium needed for atomic bomb development. Lintott introduced the first high beam current equipment based on the isotope separator concept. This original equipment was capable of producing very high beam currents at very low energies. In 1970, Lintott delivered initial systems capable of producing 5-15 milliamps of boron ions with a maximum energy of 40 keV. These very early systems were delivered without useful end-stations and users designed their own wafer handling hardware. In attempting to increase the ion energy somewhat, these users often designed a second accelerator stage called a 'post accelerator' into these end-stations, increasing total ion energy to 50 to 80 keV. Utilizing the post-acceleration concept, Lintott introduced the Series III model in 1976, a system capable of energies up to 400 keV.

Varian also introduced a high-current implanter in 1976. It was designated the Model 200-1000 and was capable of producing 1000 microamp ion beams at up to 200 kilovolts. That machine was subsequently replaced by Model 8010 (80 kilovolts at 10ma)—first shipments of which began in 1980. Ultimately, suppliers such as Eaton, Balzers, Ulvac, Nissin High Voltage, Shinko Seiki, Hitachi, and Veeco entered the high current market. Balzers introduced its Model 310 high-current equipment in 1979. (discontinuing it in 1982). Eaton-Nova announced the NV10 series in 1979. Ulvac introduced a system in 1979, and shipped its first system in 1983. Veeco introduced its VHC-120 in late 1982, with first shipments two years later.

The 1985 recession had a significant impact on competition in the North American ion implanter market. GCA left the market and Varian-Extrion and Eaton-Nova were locked in intense competition. At the same time Japanese companies began to make aggressive moves to penetrate the implant equipment market. Nissin High Voltage, Shinko Seiki and Hitachi all offered state-of-the-art high current implanters. Ulvac gained significant market share and emerged as the world's number four supplier of implantation equipment.

Ion implanters are very complex machines. Operators must make numerous decisions in real time. Sometimes simple mistakes can result in significant damage to either the machine itself or, at minimum, to the wafers being processed. Consequently, there has been substantial pressure from users to have sophisticated computer controls added. The industry trend has been towards so-called 'one-button' machines, that is, ones that can be turned on and be fully operational with the push of just one button. Extrion, in cooperation with one of its largest customers, began an aggressive program in the mid seventies to simplify and automate its systems. The results of this development first appeared on the open market with Extrion's introduction of the Model 8010.

Simplicity of operation has now been effectively addressed by all vendors, and all machines now have sophisticated controls. These improvements have been instrumental as implant applications have evolved into highly uniform and precise methods.

This trend is also being driven by the need for factory integration. In an integrated factory, production equipment must be capable of being digitally controlled. In order for this to occur, however, systems must also be capable of providing easily reproducible, assistance-free results.

These sophisticated implanters must be capable of monitoring all important internal functions. They must be able to automatically make appropriate process corrections or shut themselves down. Additionally, they should be able to interface with automated guided material delivery vehicles or SMIF systems.

Floor space is another issue affecting the design of ion implanters. Ion implanters are very large machines. Any design innovation which reduces floor space requirements will save substantial clean room costs in construction, operation, and maintenance of the wafer fab. As a typical example, the Varian 8010 high-current implanter requires only 136 square feet.

4.5.1.2 Technology

Ion implantation systems evolved from linear accelerator technology developed for atomic research programs during World War II. The process can be visualized in terms of a high velocity projectile becoming embedded into a block of material. Atoms of a dopant material are converted to ions (the projectile) in an ion source. These ions are extracted from the ion source and accelerated by a high voltage electric field (the gun barrel) to very high velocity. The ions then travel a short distance and strike the surface of the wafer. As they impact the wafer surface the ions immediately begin to collide with the atoms of the wafer, careening from one atom to another. These collisions result in the creation of a great deal of damage to the wafer on the atomic scale. In each collision between the projectile atom and the wafer atom, the projectile loses some of its forward momentum and slows down. Eventually the projectile atom will loose all of its energy and come to rest within the wafer at some distance from the surface.

The engineering, physics and material science involved in ion implantation equipment and processes are complex and much of the detailed description is beyond the scope of this treatise. We will, however, attempt to impart enough information to give the user a basic understanding of the processes involved.

4.5.1.2.1 Ion Implantation Processes

First, let us examine events that occur as a high velocity ion impacts the wafer surface and then follow subsequent events as the ion eventually comes to rest. One must visualize this process from an atomic scale as shown in Figure 4.5.1.2.1-1.

The silicon atoms of the crystalline silicon wafer are arranged in a regular rectangular arrangement called the crystal lattice. Each silicon atom is attached to its nearest neighbor by an energy field due to its valance electrons. Orbiting each silicon atom are the remainder of the electrons making up the atomic structure of the silicon lattice. As the high-velocity, positively-charged ion approaches this silicon array, coulombic forces begin to come into play. These are the normal electronic forces between the approaching ion and the individual silicon atoms and electrons in the wafer.

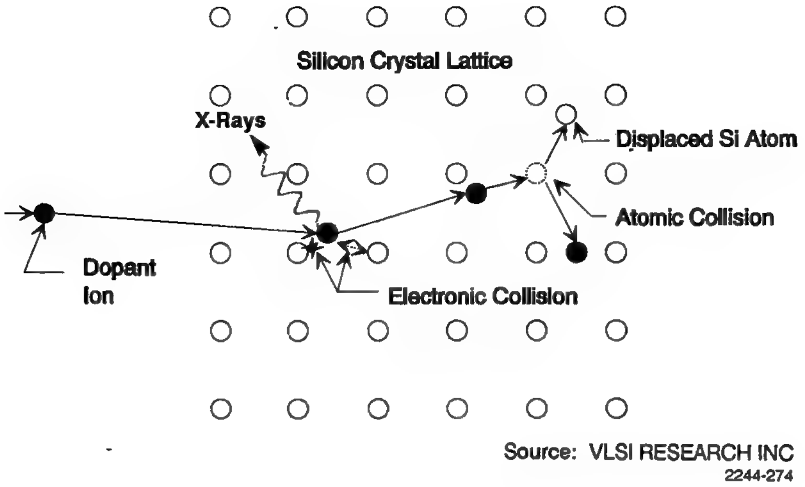

Figure 4.5.1.2.1-1

Ion-Lattice Interactions

Initially, the strongest reactions are between the approaching ion and the electrons. These reactions result in the incoming ion losing some of its energy in elastic collisions with the electrons. It is these reactions that give rise to Bremstrallung radiation and soft X-rays emitted from the wafer surface. At this early stage, only a few collisions with silicon atoms occur.

As the ion penetrates further into the wafer surface it loses additional energy in electronic collisions. As it slows down, it begins to spend more time in close proximity to a silicon atom and the probability of collision with an atom increases. Figure 4.5.1.2.1-2 shows the relative electronic and atomic collision probability as a function of incoming ion energy.

Upon collision with a silicon atom, the ion may cause the silicon atom to be removed from its lattice position. As this process proceeds to its conclusion, many silicon atoms are ejected from their lattice sites, resulting in physical damage to the crystalline structure of the silicon crystal (most of the lattice damage occurs near the end of the ion's trajectory—see Figure 4.5.1.2.1-3). The ion eventually comes to rest at some depth within the wafer.

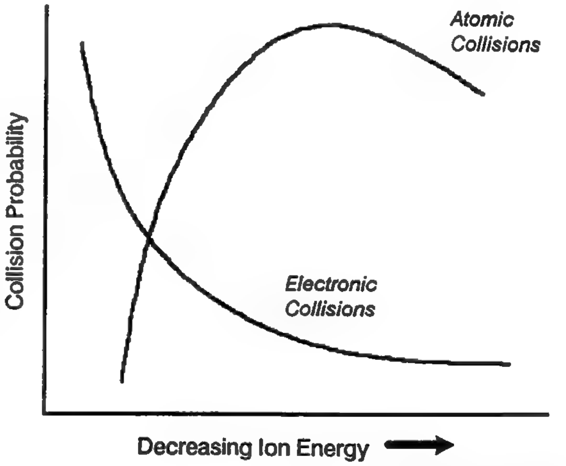

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Figure 4.5.1.2.1-2

Relative Collision Probability for Electron and Ion Collisions

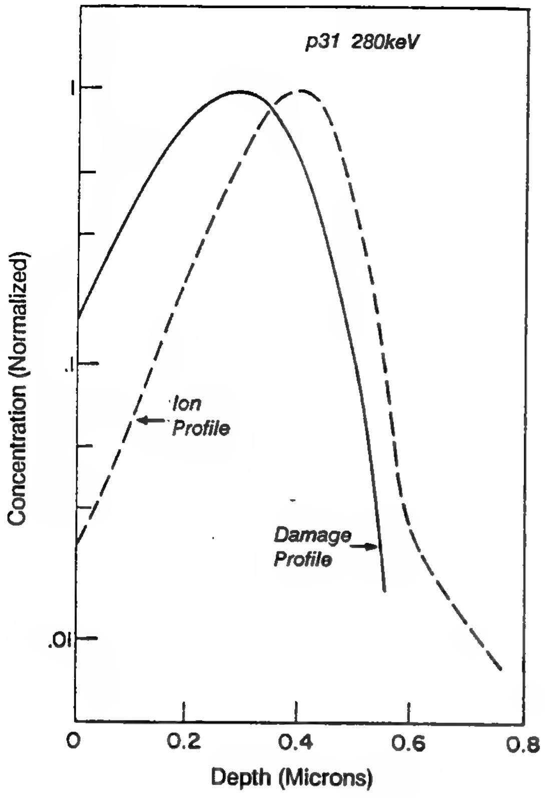

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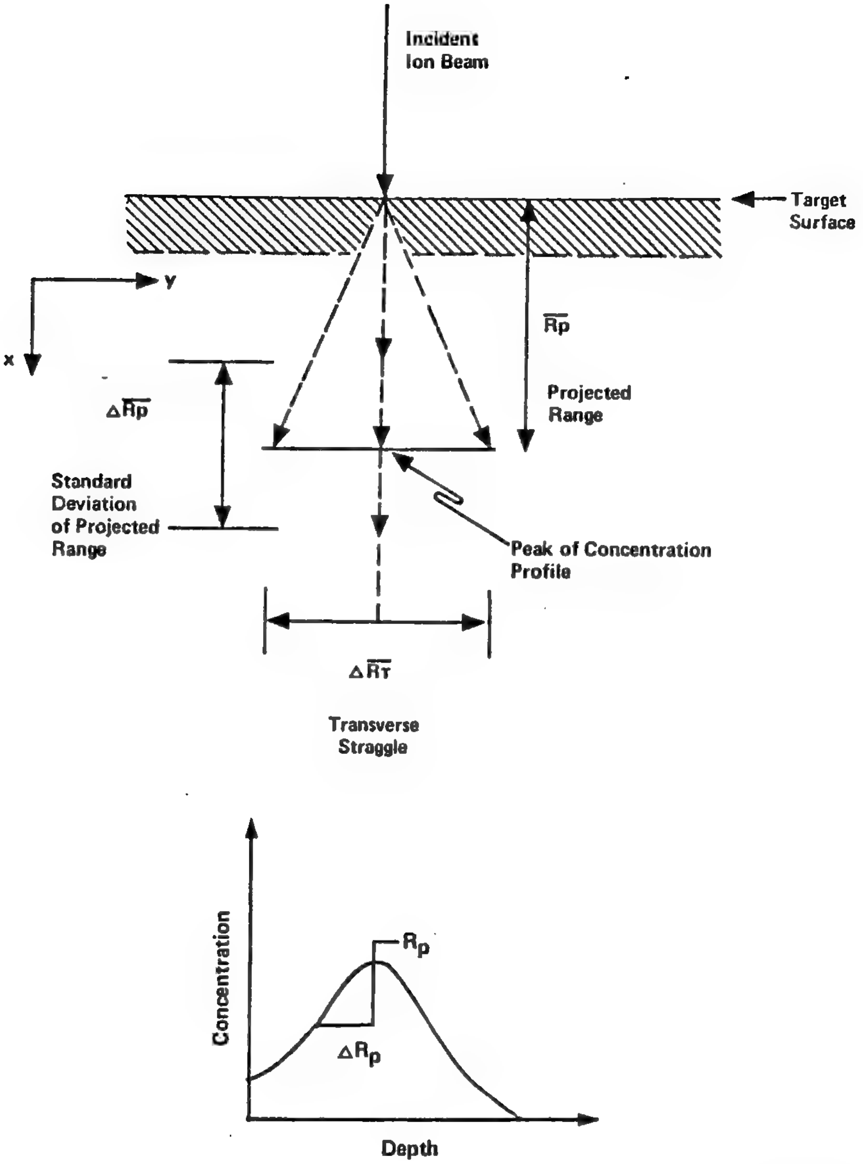
Figure 4.5.1.2.1-3

Relation of Implant Damage Profile to Implanted Dopant Profile

In 1963, at the University of Aarhus, Linhard, Scharff and Schiott (LSS) showed theoretically that the resulting distribution of implanted ions is Gaussian, with the maximum occurring at a depth R_p with a standard deviation of ΔR_p (See Figure 4.5.1.2.1-4). The actual resulting dopant distribution depends upon several parameters. These parameters are ion energy, ion mass, substrate type, ion current and crystal orientation. Figures 4.5.1.2.1-5 and 4.5.1.2.1-6 show calculated and measured distributions of various energy boron ions implanted in silicon. Resulting total dopant concentration is controlled by the total number of ions implanted. The total number of ions implanted per cm^2 is called the dose. Figure 4.5.1.2.1-7 shows the distribution profiles of arsenic implanted in silicon at 50 keV with doses of 1 x 10^{16}, 1 x 10^{15}, and 1 x 10^{14} ions per square centimeter. Crystal orientation also has a significant impact on the resulting implanted profile. The upper part of Figure 4.5.1.2.1-8 shows the effect of orienting the crystal surface in such a way as to align crystalline planes with the incoming ions. It is easy to see that fewer atoms are exposed to collisions with implanted ions and that there is much more open space than in the case of a crystal oriented in an 'off-axis' or 'random' direction (as seen the lower part of the figure). When the surface of the wafer is aligned with the incoming ion beam, the implanted ions penetrate considerably deeper than in the 'random' orientation case as shown in Figure 4.5.1.2.1-9.

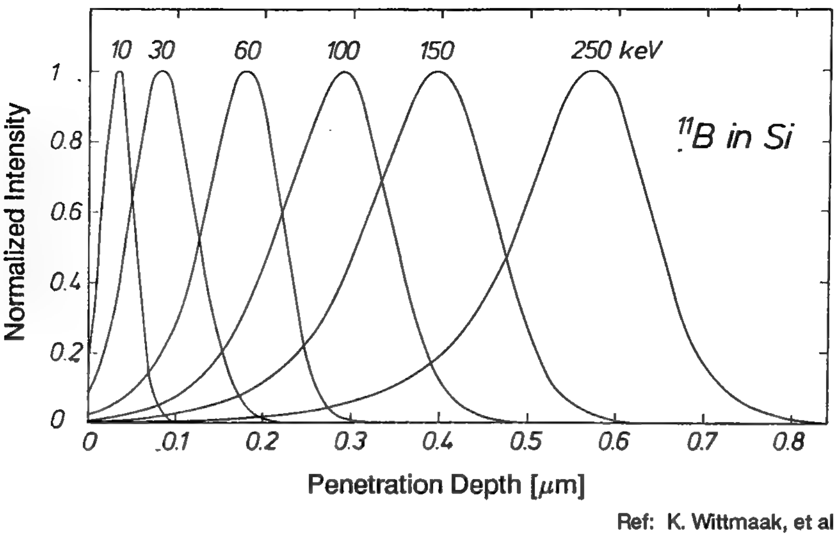
As we've noted, the implantation process causes considerable physical damage to the substrate. In addition, implanted atoms generally are not located in proper dopant sites within the crystal lattice and are not electrically active. Both of these problems are cured by a subsequent annealing process in a standard diffusion furnace. Details of the annealing process are quite complicated and depend on the dopant distribution ultimately desired. For example, if the desire is only to repair the implantation damage and activate the implanted ions, only the minimum temperature is required to anneal the damage and activate all the implanted ions. The specific annealing time and temperature is determined experimentally for the specific application in mind. This process is widely used for MOS threshold adjustment. However, many processes require deep junctions, in which case a drive-in diffusion process is used. This drive-in process is nearly identical to the normal diffusion process, except that the implantation step takes the place of the predep step. Figure 4.5.1.2.1-10 shows the resultant carrier concentration after implanting silicon with 1 x 10^{14} boron ions per cm^2 and annealing the wafer at various temperatures from 300 °C to 900 °C. The increase in peak concentration of carriers


Incident Ion Beam
Target Surface
Y
X
$\overline{R_p}$
Projected Range
$\Delta\overline{R_p}$
Standard Deviation of Projected Range
Peak of Concentration Profile
$\Delta\overline{R_T}$
Transverse Straggle
Concentration
R_p
ΔR_p
Depth

Ref: Fair
2244-277

Figure 4.5.1.2.1-4

Graphical Representation of Variables Used in LSS Theory



Ref: K. Wittmaak, et al
2244-278

Figure 4.5.1.2.1-5

Theoretical Distribution Profiles for Boron Implanted at Various Energies in Silicon

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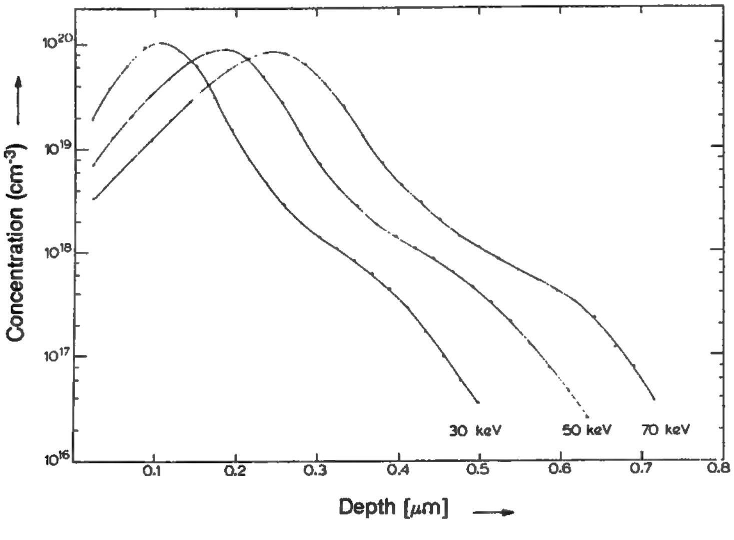
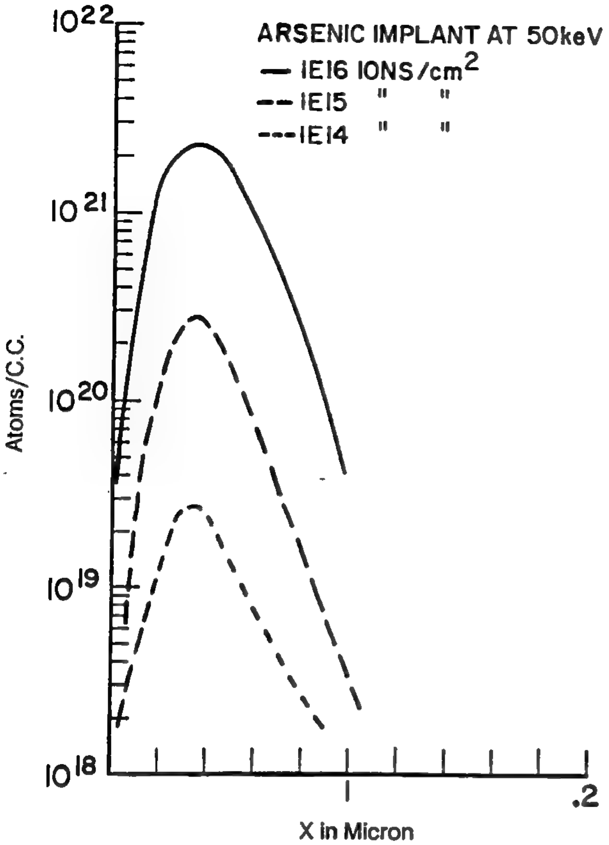


Ref: W.K. Hofker, et.al
2244-279

Figure 4.5.1.2.1-6

Measured Profiles of Boron Implanted in Silicon at 30,50 & 70 keV



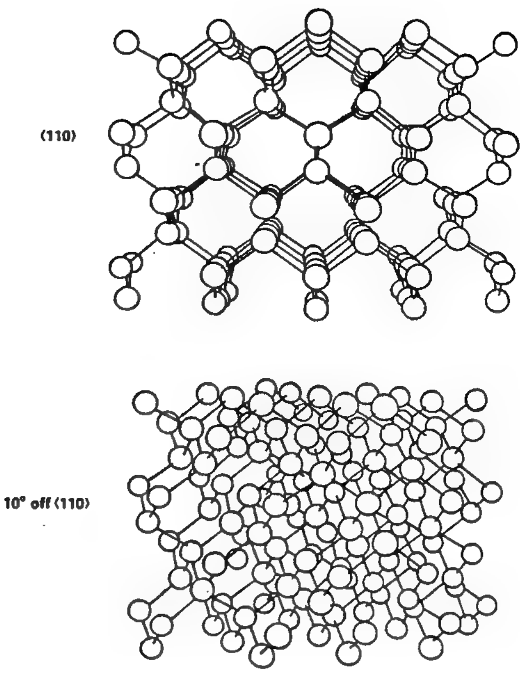
Ref: J.C.C. Tsai, et al
2244-280

Figure 4.5.1.2.1-7

Calculated Profiles of Arsenic Implanted in Silicon with Different Doses

after each increase in annealing temperature is attributed to the elimination of a number of complicated types of defects and defect clusters. If the implanted dose is very high, the underlying substrate material can be so severely damaged as to be nearly amorphous–that is, it will have no short range order.

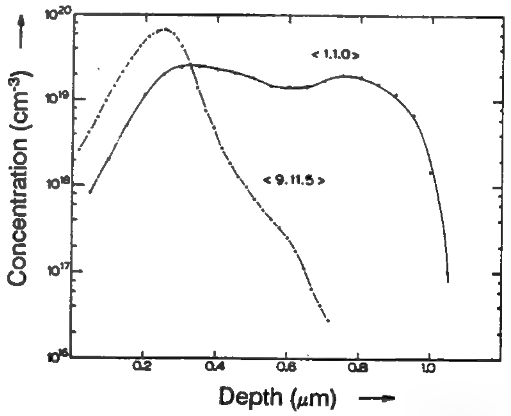
In such cases a phenomenon occurs upon annealing that is similar to an epitaxy process. This 'solid state epitaxy' process restores the crystalline order by regrowing the silicon lattice from the inside toward the surface.



Ref: Fair
2244-281

Figure 4.5.1.2.1-8

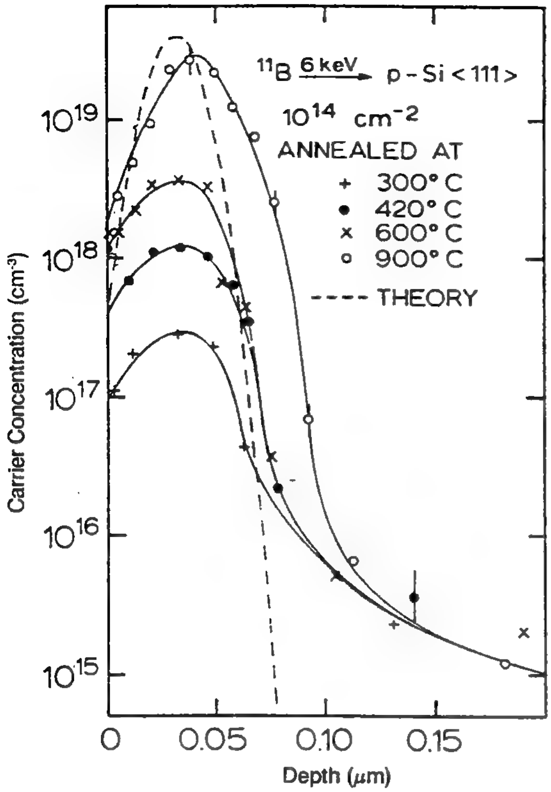
Atomic View of "Aligned" & "Random" Directions in Silicon



Ref: W.K. Hofker, et al
2244-282

Figure 4.5.1.2.1-9

Distribution of Boron Implanted at 70 keV into Silicon in the "Aligned" & "Random" Directions



Ref: R. Bader, et al
2244-283

Figure 4.5.1.2.1-10

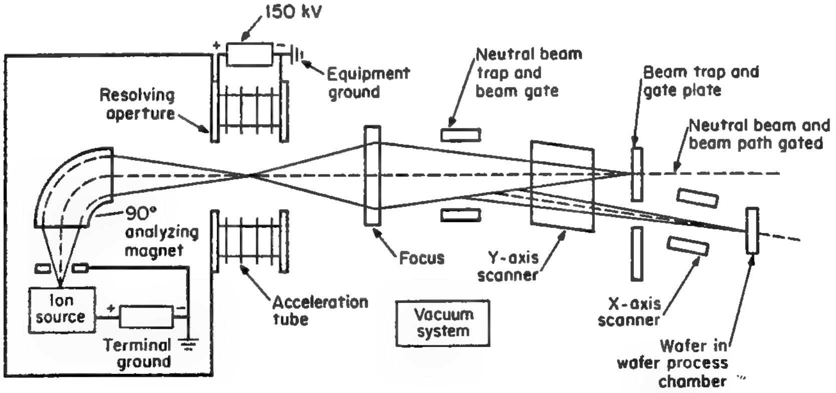
Carrier Activation as a Function of Anneal Temperature

4.5.1.2.2 Ion Implantation Equipment

As mentioned, early ion implanters were particle accelerators or isotope separators originally intended for use in atomic physics and chemistry research. These early accelerators were usually capable of producing only very small beam currents of light ions at low to intermediate energies. Atomic physicists generally were only interested in accelerating hydrogen or helium ions in these systems, allowing them to strike a very small spot on the target material.

In contrast, isotope separators were designed to produce abundant amounts of heavy ions at extremely low energies—but again, these researchers were only interested in small target areas. Machines had to undergo significant modification to allow them to accelerate heavy ions to the required energies and to distribute these ions *uniformly* over the surface of the wafer. Figure 4.5.1.2.2-1 shows a schematic outline representation of an early ion implanter.

Today's ion implantation systems have not undergone significant changes from these early systems. On the left of Figure 4.5.1.2.2-1, ions are created in the ion source.



150 kV
Equipment ground
Resolving aperture
90° analyzing magnet
Ion source
Terminal ground
Acceleration tube
Focus
Vacuum system
Neutral beam trap and beam gate
Y-axis scanner
Beam trap and gate plate
Neutral beam and beam path gated
X-axis scanner
Wafer in wafer process chamber

Ref: David J. Elliott
2244-284

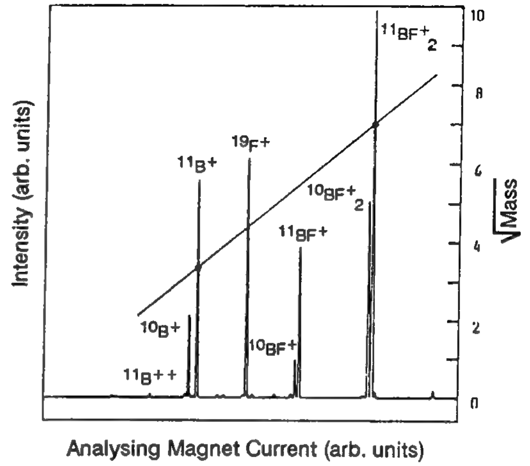
Figure 4.5.1.2.2-1

Simplified Schematic of a Typical Ion Implanter

A beam of ions is extracted from the source by a small electric field. This extracted ion beam usually consists of many different atomic species in addition to the desired dopant atoms. For example, a typical ion source using boron trifluoride as a source gas may produce boron ions, fluorine ions, boron-fluorine molecules, nitrogen and oxygen ions and molecules, as well as various metal and impurity ions and molecules from the material in the walls of the ion source. In addition, these individual atoms and molecules are made up of isotopes of each of these atoms and molecules, as shown in Figure 4.5.1.2.2-2.

The analyzing magnet of the implanter eliminates all unwanted ions and molecules from the ion beam and allows only the desired isotope of the dopant atom to pass into the accelerator tube. The strong magnetic field within this analyzing magnet applies a force on each ion that is proportional to the ion's energy and charge. It is always at right angles to its instantaneous direction of motion. The result is that each type of ion follows a slightly different arc through the analyzer. Light, fast moving ions will be deflected much more than heavy, slow moving ions. This results in a separation of ions as they pass through the magnet, much like the dispersion of light passing through a prism (see Figure 4.5.-1.2.2-3).

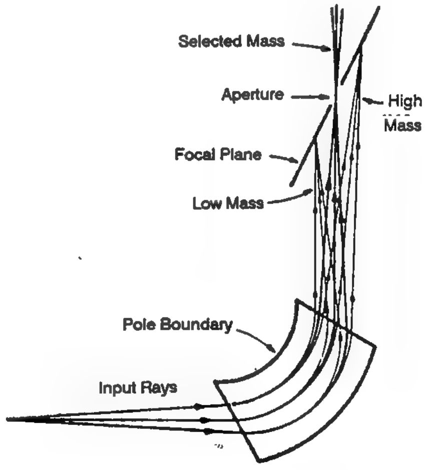
The selected ions are then refocused with an electrostatic or magnetic lens and allowed to pass into a beam-shutter/neutral-trap device. This device (usually a set of parallel plates with an applied DC voltage) either deflects the ions onto a water cooled metal plate called the shutter, (or beam stop), or they are deflected through a small angle and allowed to travel further down the implanter. Neutral (uncharged) dopant atoms are created by a charge exchange process at every point in the flight path of the ion. Since neutral ions cannot be deflected by electrostatic or magnetic devices, and therefore cannot be distributed uniformly over the wafer, they are allowed to travel straight through the neutral filter and out of the deflected beam.



Ref: Glawischnig, et al
2244-285

Figure 4.5.1.2.2-2

Typical Boron Spectra Produced by an Ion Source with BF$_3$ Feed Gas



Ref: Purser et al
2244-295

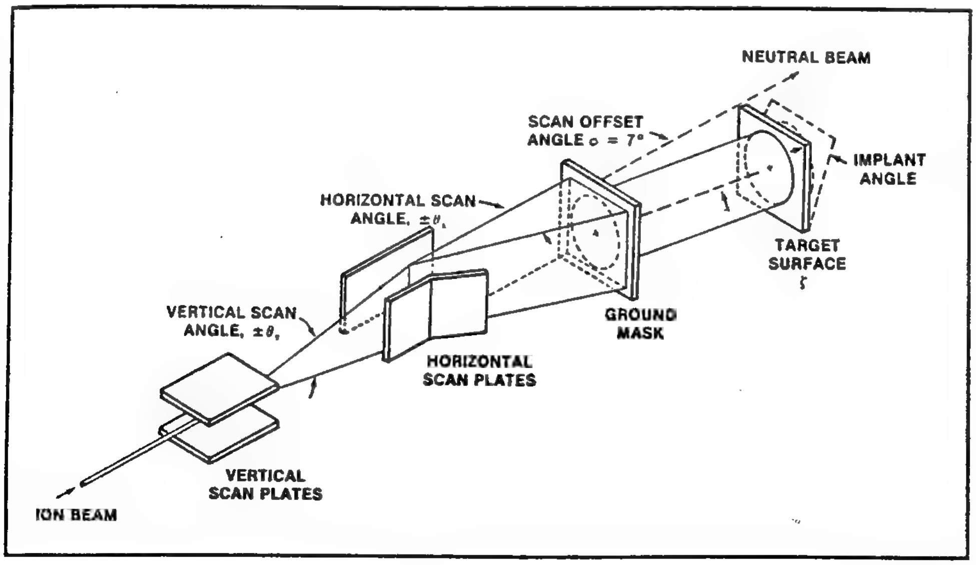
Figure 4.5.1.2.2-3

Magnetic Analyzer

The remaining charged ions then pass through a device called a beam scanner. Typically, the scanner is made up of two sets of parallel metal plates positioned at 90-degree angles from one another. An alternating voltage with a triangular wave pattern is applied to one of the plates in each set. A triangular wave potential 180^0 out of phase with the first wave is applied to the opposite plate in the set. These carefully controlled alternating voltages cause the ion beam to be uniformly deflected back and fourth in a straight line across the wafer surface. The second set of plates operate in exactly the same way, causing the previously scanned 'line' to be scanned in a perpendicular direction. This scanning system distributes the ions uniformly over the wafer surface in the same way that an electron beam in a television tube is scanned over the tube's surface. A typical scanner system design is shown in Figure 4.5.1.2.2-4.

We've noted so far that ion energy, ion species, and the ion current density are selected by adjustment of the various subsystems of the implanter. The only remaining variable, the implanted ion dose, must be measured and controlled at the wafer's surface. This is done by simply electrically isolating the wafer from the chamber so it will collect charge; the total charge captured by the wafer surface is then measured with a special integrating ammeter called a beam current integrator.

Since the charge carried by each positive ion is equal to and opposite in value to the charge of an electron (an ion is created by removing an electron), one needs only to calculate the total charge that will be carried by the desired number of ions. With a charge on the ion of 1.6×10^{-19} coulombs, a desired dose of 1×10^{15} dopant ions will require that a total charge of 1.6×10^{-4} coulombs be collected. This value is programmed into the beam current integrator and the implanter is turned on. When this predetermined charge is collected, a signal is sent from the current integrator to the beam shutter subsystem. The beam shutter



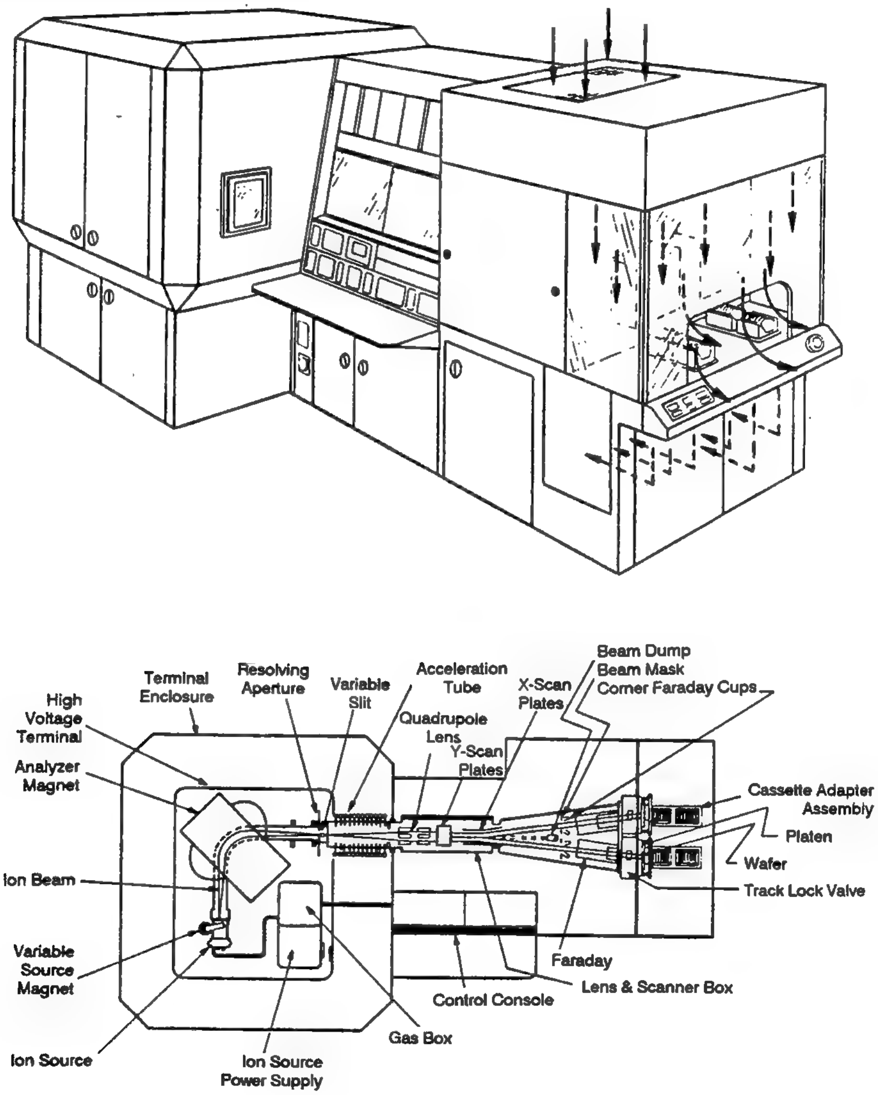
Ref: White
2244-286

Figure 4.5.1.2.2-4

Example of an Electrostatic Scanning System

then removes the DC deflection voltage from the plates, allowing the ion beam to travel straight into the beam stop and shutter or stop the implant process. The implanted wafer is then moved out of the implant position and is replaced by the next wafer.

In this way, exactly the same number of ions are implanted into each wafer's surface in sequence. This is the basic single wafer in-line process implanter design. Figure 4.5.1.2.2-5 shows a typical implanter incorporating all of the above components. In this system, two separate wafer chambers or end-stations are used to improve throughput. While one end-station is being serviced or reloaded with cassettes, the other end-station can continue processing.


High Voltage Terminal
Terminal Enclosure
Resolving Aperture
Variable Slit
Acceleration Tube
Quadrupole Lens
Y-Scan Plates
X-Scan Plates
Beam Dump
Beam Mask
Corner Faraday Cups
Analyzer Magnet
Cassette Adapter Assembly
Platen
Wafer
Track Lock Valve
Ion Beam
Variable Source Magnet
Faraday
Lens & Scanner Box
Control Console
Gas Box
Ion Source
Ion Source Power Supply

Ref: Varian
2244-287

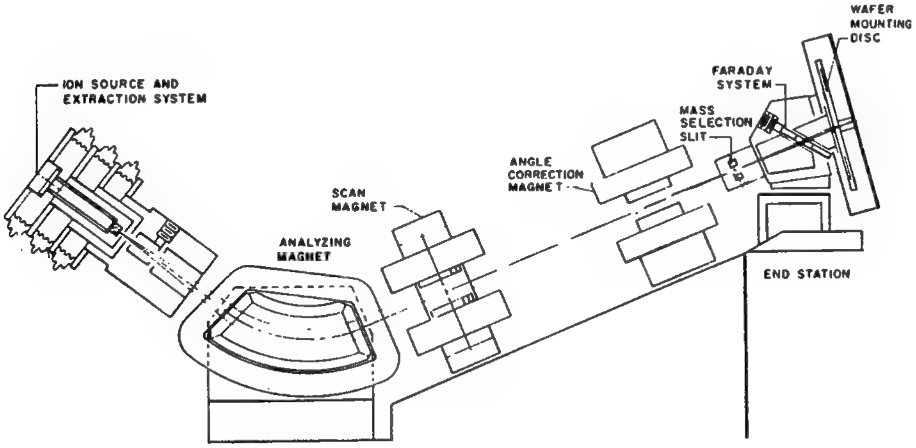
Figure 4.5.1.2.2-5

Varian Model 350D MCI Implanter

All implanter designs contain similar subsystems. Lens, scanner, and target chamber design details may vary among but all designs contain the basic fundamentals outlined above. Certain designs incorporate part of the beam scanning mechanisms and the wafer motion into the target chamber, resulting in a batch process. In these systems, the wafers are placed on a circular plate or on the circumference of a drum and the plate or drum is rotated at a fixed rotational speed. The electrostatic scanning is done in one direction only while the wafer is rotated through the scanned beam. This method is called hybrid scanning. Figure 4.5.1.2.2-6 shows one example of such a system using a rotating disk.

Integrating the beam current at the wafer surface is not simple. At the instant the ion strikes the wafer surface, electrons are ejected from the wafer due to ionization and other effects. If these electrons are allowed to escape, an electronic unit of charge will be carried away with each escaping electron, resulting in a significant error in the total ion charge collected. To overcome this problem, a long tube is placed in front of the wafer. This tube is electrically connected to the wafer, creating a Faraday cup into which the ion beam passes. A shorter tube, called the suppressor ring, is placed just in front of the Faraday cup. The suppressor ring is maintained at a negative potential of 10 to 100 volts. Electrons that manage to escape from the wafer will be repelled by the suppressor ring and collected within the walls of the Faraday cage.

Another important, but more subtle, effect can occur at the wafer surface and can result in damage to the devices being implanted. Typically, photoresist is used as the implant mask to delineate the wafer surface areas to be implanted. Often this photoresist is applied over device regions containing silicon dioxide films. Photoresist is not a conductor, and therefore can accumulate charge as it collects implanted ions. Since this accumulated charge cannot readily escape, a voltage will quickly build up across the oxide as the implanted ions act as



Ref: Varian
2244-288

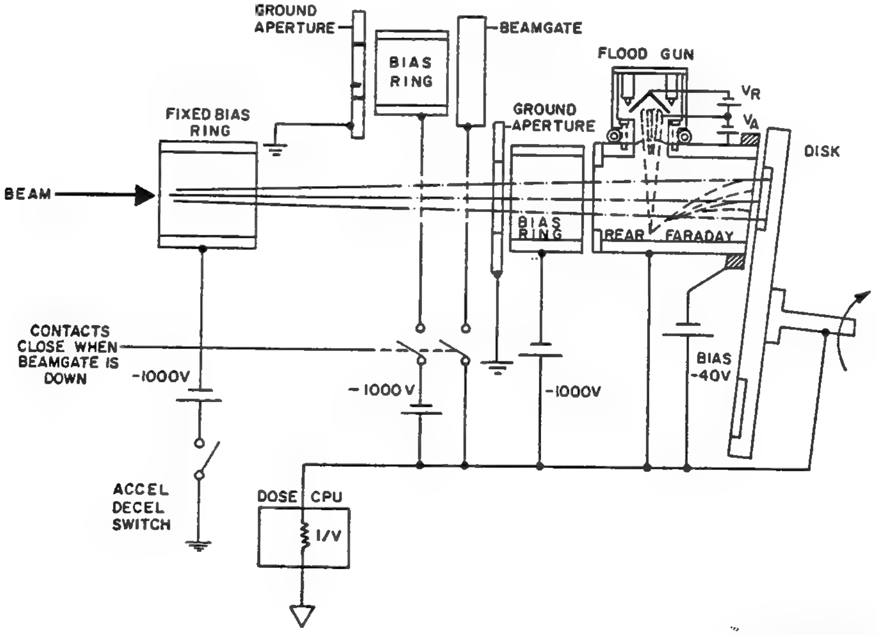
Figure 4.5.1.2.2-6

Varian's 350D High Current Implanter Using Rotating Disk End Station Design

one plate of a capacitor. As this voltage increases, a level will be reached which will exceed the dielectric strength of the oxide. The resulting breakdown can cause device damage. To prevent this breakdown, a flood of electrons is allowed to neutralize the collected charge. Since all electrons from the flood gun are created and collected within the Faraday cup, the wafer will receive no net charge from the electron flood. This arrangement can be seen in Figure 4.5.1.2.2-7.

One of the most important attributes of an ion implanter is its beam current capability. All implanter subsystems play a role in the production of the ion beam, but one component, the ion source, probably plays the most important role. It is this device that determines both the type and quantity of ions that can be implanted. Early implanters utilized a very simple design concept called an RF ion source. In this design, shown in Figure 4.5.1.2.2-8, a small, partial pressure of gas containing atoms and molecules of the desired species is introduced into a quartz tube. The gas is ionized in an RF discharge by applying an RF field through a coil wrapped around the tube. Ions are then extracted from the source by an electrode placed close to the source aperture, and the ions are directed into the accelerator column or into the mass analyzer. This type of source is limited to ions that can be created from a source gas such as BF_3, and is generally not capable of providing more then a few microamperes of beam current.

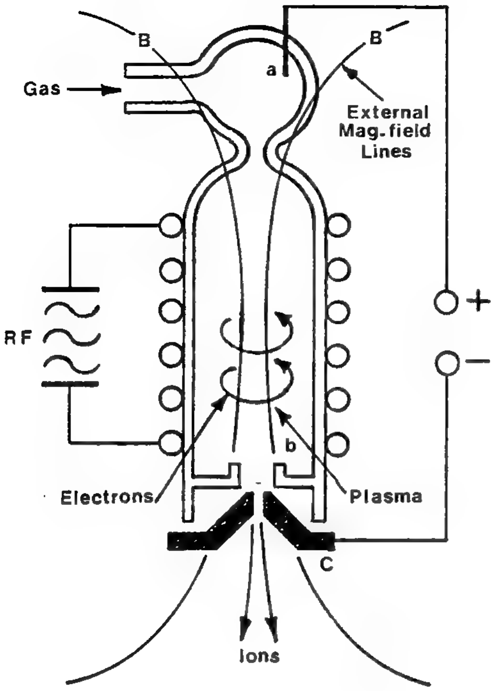
A source design that was originally used in isotope separators has now become popular for high current implanters. This source, known as the Freeman source (Figure 4.5.1.2.2-9), is capable of producing ions


GROUND APERTURE
BEAMGATE
BIAS RING
FLOOD GUN
VR
VA
FIXED BIAS RING
GROUND APERTURE
DISK
BEAM
BIAS RING
REAR FARADAY
CONTACTS CLOSE WHEN BEAMGATE IS DOWN
-1000V
- 1000 V
-1000V
BIAS -40V
ACCEL DECEL SWITCH
DOSE
CPU
I/V

Ref: White
2244-289

Figure 4.5.1.2.2-7

Implanted Charge Collection Device with Surface Charge Neutralization Capability



Ref: Stephens
2244-292

Figure 4.5.1.2.2-8

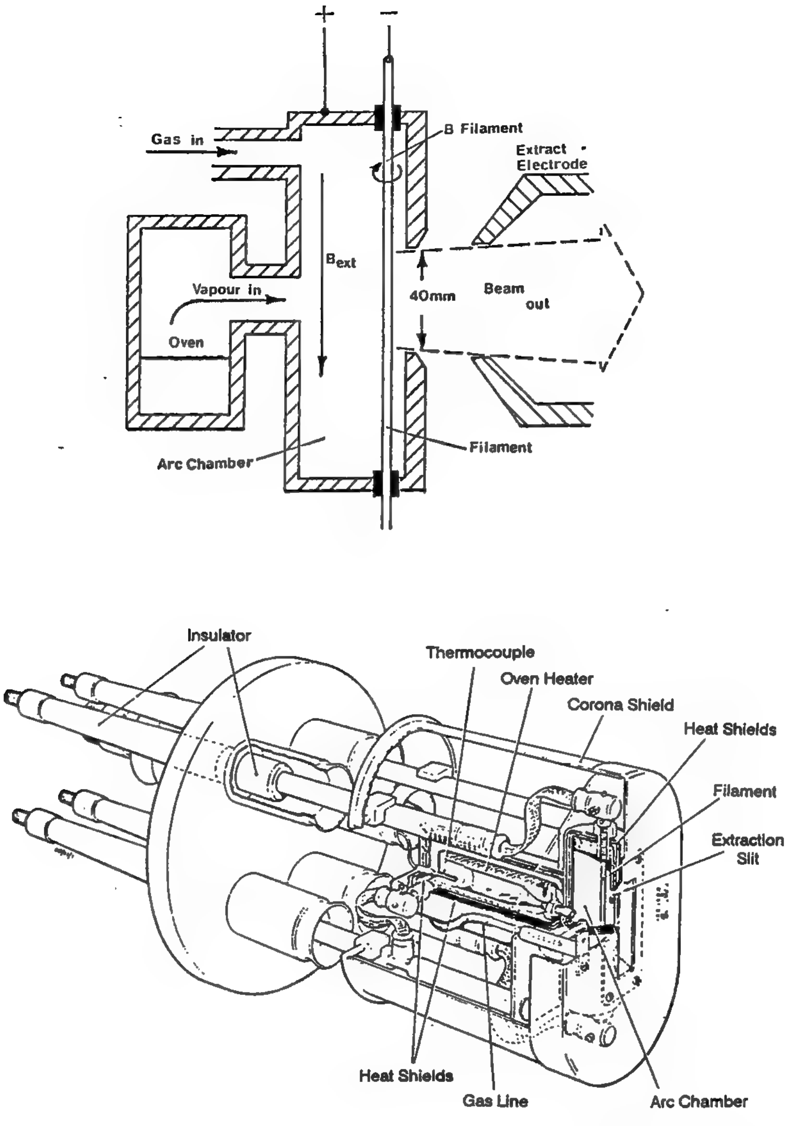
R.F. Ion Source

from either a gas or a solid material and can generate intense ion beams of 25 milliamperes or more. This design incorporates a hot filament to create an intense source of electrons. A potential of a few hundred volts is applied between the filament and the source housing. This potential causes the electrons to gain enough energy to cause ionization of the source gas upon collision with the gas atoms. A small magnetic confinement field parallel to the filament is created by an electromagnet placed outside the source housing. The magnetic field helps confine electrons to spiraling paths around the filament in their attempt to escape to the positively charged chamber wall. This confinement greatly increases the probability of collision with the source gas atoms and increases ionization efficiency of the source. Dopants that are not easily produced from gaseous sources can be created from solid materials by heating and vaporizing the solid material in a small oven attached to the rear of the source. Solid arsenic could, for example, be used in place of the highly toxic gas arsine. In this case an easily ionized carrier gas, typically helium or hydrogen, is used to sustain the discharge.

The Freeman ion source design produces an ion beam that is rectangular in shape, typically 1 or 2 millimeters by 20 to 40 millimeters. This rectangular beam can be efficiently separated in a magnetic analyzer.

In the ion implanter designer's quest for high-current ion beams, a better understanding of ion optics and ion beam transport had to be developed. Ion beams are, by definition, beams of charged particles. General physics teaches us that there are electrostatic forces, called coulombic forces, that exist between two charged particles. If these charges are equal in sign, the force will be repulsive. Coulombic forces play a very important role in the transportation of intense, high-current ion beams. These forces give rise to a phenomena called 'space charge blow up'. Space charge causes intense ion beams to rapidly increase in size. The beam is then more difficult to control and ions are quickly lost to the walls of the implanter. To combat this effect, special electrostatic and magnetic lenses are incorporated to focus the ion beam throughout the beam's path to the wafer. These lenses behave similar to optical lenses. However, the attempt to focus the beam to a smaller size will cause the space charge effect to increase in magnitude, opposing the attempt to focus.

An intense ion beam can also be thought of as a filament or 'wire' carrying a large current—a form which gives rise to further complications. This large current-carrying 'wire' induces electrostatic and electromagnetic charges on its surroundings, causing ion lenses to 'misbehave' and causing other 'passive' components to exert steering forces on the ion beam. This dynamic interaction

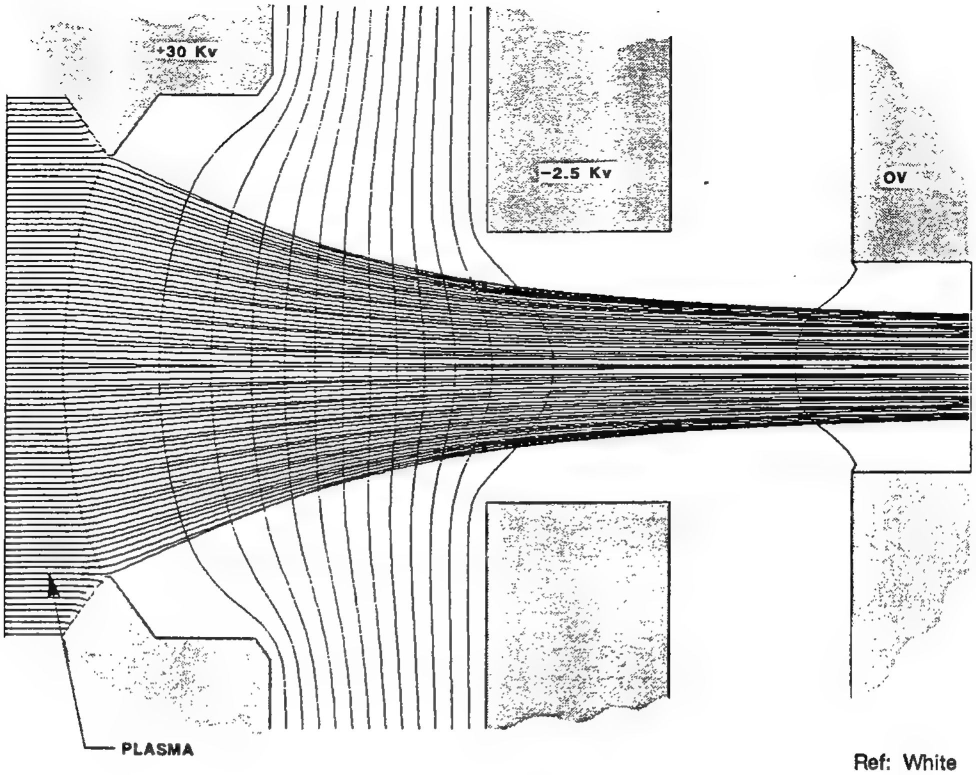

+
−
Gas in
B Filament
Extract
Electrode
Bext
Vapour in
Oven
40mm
Beam out
Arc Chamber
Filament
Insulator
Thermocouple
Oven Heater
Corona Shield
Heat Shields
Filament
Extraction Slit
Heat Shields
Gas Line
Arc Chamber

Ref: Stephens
2244-293

Figure 4.5.1.2.2-9

Freeman Ion Source

of the ion beam with its surroundings and with itself is complicated and has given rise to intensive theoretical and experimental modeling. Recent advances in computer modeling of ion beam transport phenomena have helped solve some of these complicated effects. Figure 4.5.1.2.2-10 shows a typical computer simulation plot of an ion beam being extracted from an ion source. Today's implanters typically have five or six ion-focusing devices. Accelerating columns typically incorporate self-focusing as the ion beam energy is increased.



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2244-294

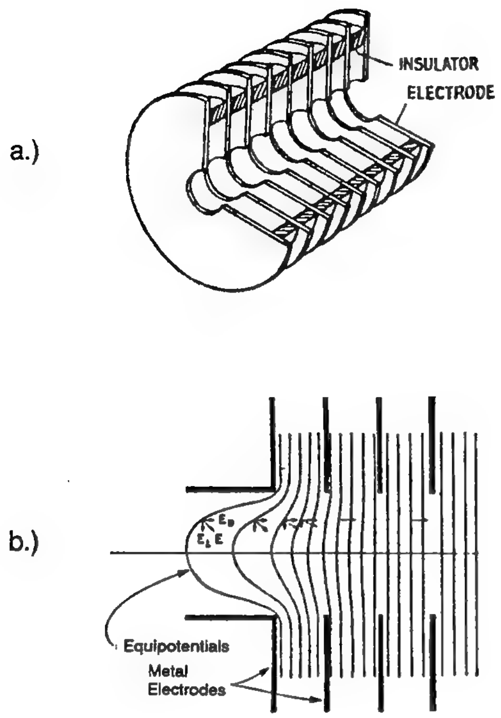
Figure 4.5.1.2.2-10

Computer Model of an Ion Beam Extractor

Except for better materials and cooling designs, magnetic mass analyzers have not undergone a great deal of basic design change. One significant development has been the use of the entrance and exit edges of the magnet to cause 'fringe field' focusing of the ion beam. The mass analyzer continues to be one of the largest, heaviest and most expensive components of an ion implanter. It is also one of the largest power consumers. Short of using superconducting magnets, no significant design changes are foreseen.

Accelerator column designs have been improved through the use of computer simulation, better materials technology, and by better and higher speed vacuum pumps. Early accelerator column designs were usually assembled from many simple dough-nut-shaped plates insulated from one another by a short (1 or 2 cm) length of glass or a ceramic tube (Figure 4.5.1.2.2-11a). Vacuum integrity was maintained by an O-ring placed between each plate-and-tube section. Each plate in the series was electrically connected to the next plate by a 10 to 50 megohm resistor, forming a voltage divider arrangement. The total accelerating potential was applied across this series of gaps.

The voltage divider distributed the potential drop equally across each of the gaps in the series (see Figure 4.5.1.2.2-11b.). Modern accelerator columns follow the same basic design concepts but the individual plates are now machined into special shapes to allow self-focusing. In addition, many designs now use a special epoxy to glue the metal plates to the insulators. The insulator itself



Ref: Purser et al
2244-296

Figure 4.5.1.2.2-11

Accelerator Column

may also be made of the same epoxy material. Modern higher-speed vacuum pumps can create a higher vacuum in the accelerator tube, allowing larger voltage drops across each gap. This results in the need for fewer gaps and can significantly reduce the overall size of the system.

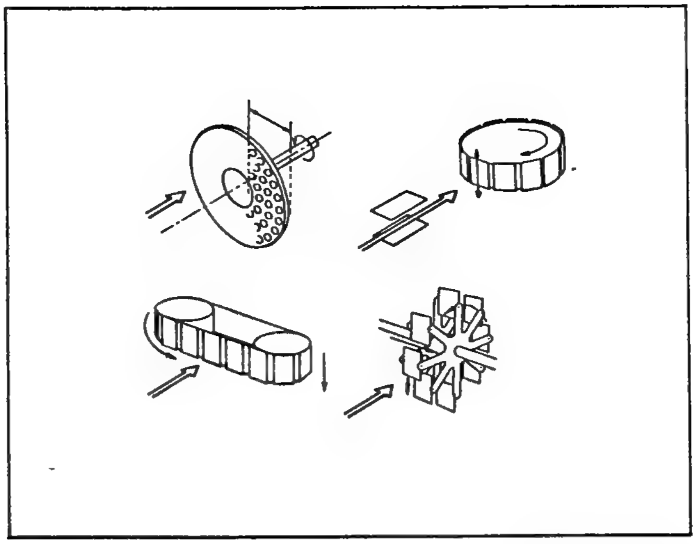
Another important subsystem is the scanner and end-station system. The design shown in Figure 4.5.1.2.2-4 scans the ion beam in two directions and is generally used in single wafer systems. This type of scanning system requires that beam size (cross sectional area) be as small a possible as it strikes the wafer. This is in conflict with using large beam currents for two reasons: first, strong focusing of high current beams increase the space charge effects; second, high intensity beams striking small spots can create tremendous local heating of the wafer. This local heating can easily be sufficient to melt the wafer. For example, assume a beam current of 5 milliamps, an ion energy of 100 keV and a spot size 2 mm in diameter. The total instantaneous energy density in this 3 mm^2 spot is given by the formula:

$$P = I \times V = 5 \times 10^{-3}\ amps \times 100 \times 10^{3}\ volts = 500\ watts.$$

or approximately 17,000 watts per cm^2.

Even averaging this energy density over a 200 mm wafer and using efficient wafer cooling (not a simple task in a vacuum), damage is difficult to avoid. Hence, electrostatic scanning is used only in low and medium current implanters and is effective only up to a few hundred microamperes. High current machines use hybrid scanning to overcome this difficulty. Figure 4.5.1.-2.2-12 shows several methods of providing hybrid scanning. In each case the ion beam is scanned in one direction only and wafers are moved through the scanned beam. With this technique the beam spot can be much larger, thus lowering the instantaneous energy density on the wafer. The rectangular shape of high current beams is maintained throughout the beam acceleration and mass separation stages. The rectangular beam is then scanned in the direction perpendicular to its longest dimension. By moving all the wafers in the batch through this scanned beam, the total beam power is dissipated over all the wafers. Thus the average energy density is only a few watts—even for beam currents of 10 milliamps.

Hybrid scanning is not without its disadvantages, however. Wafers must be securely clamped to the substrate holder. Mechanical mechanisms required to produce motion in a vacuum tend to be notorious particle generators. Wafer batch sizes used in the fab are not necessarily the same as those in the end-station. Wafers are normally carried to the implanter in a cassette, requiring



Ref: Wegmann
2244-297

Figure 4.5.1.2.2-12

Hybrid Beam Scanning Methods

some type of robotic arm to transfer wafers from cassette to substrate holder. In spite of these difficulties, some form of hybrid scanning remains the best technique for high-current systems.

All electrostatic or hybrid scanning techniques have one common fault: the beam is deflected so that it strikes the wafer surface at various angles as it sweeps across the wafer surface. Recalling our discussion on channeling, we know that this angular change in implant direction can result in significant differences in depth distribution. For this reason some of the more recent implanter designs incorporate totally mechanical scanning systems. This design also eliminates some of the space charge effects resulting from electronic scanning. At the same time, however, it introduces another complex mechanical motion in the end-station.

Demands placed on the implanter vacuum system are probably as strenuous as those for any process machine in the fab. Quantities of extremely dangerous materials are used as sources of ions and many of these materials are highly corrosive. The vacuum system must be capable of pumping these toxic and corrosive gases without endangering the operator or the maintenance technician. The vacuum system must also be designed to remove these materials at the ion source and prevent them from diffusing into other sections of the implanter. Ion sources typically operate in poor vacuums, usually only a few torr. However, for efficient ion acceleration the vacuum must be much higher. Additionally, high pressures increase the probability of charge-exchange neutralization of the ion beam. For these reasons, differential pumping is incorporated across the source aperture and extractor. As the ion beam is separated in the analyzer, the unwanted beam components become embedded in the walls of the beam tube, causing sputtering, wall heating and a tendency for higher vacuum pressure in that region. The beam scanner and end-station region must be maintained at pressures of a few millitorr to reduce charge exchange and particles. The total volume of the implanter vacuum envelope is fairly large, usually requiring three or more separate vacuum pumps–one at the ion source, one between the analyzer and the post accelerator and one in the end-station. Early systems used diffusion pumps but modern machines also incorporate high speed turbo and cryopumping systems.

One additional design concept of ion implanters deserves discussion. Close examination of Figure 4.5.1.2.2-1 and 4.5.1.2.2-5 shows that the entire ion source and magnetic analyzer systems–including power supplies–are contained in an enclosure called the 'terminal,' which is raised to the accelerating potential. All of the electrical power required and all necessary controls must be transferred across this voltage. Many systems use isolation transformers to provide power and insulated rods to provide the control needed accomplish this. Newer designs use fiber optics to provide digital control to the terminal. Some systems, especially high energy machines, use a motor-driven generator system to provide electrical power in the terminal at high voltage.

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4.5.2 COMPETITIVE ENVIRONMENT

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4.5.2 Competitive Environment

The ion implant industry emerged from the three-year slump of 1985 to 1987 to achieve phenomenal growth. The market grew more than doubled in size between 1986 and 1988, and has continued to grow through 1989. The profitability picture changed dramatically as semiconductor manufacturers began paying a premium for early delivery. High-current implanters were in such short supply that only high volume purchasers received delivery.

The competitive environment for ion implanters is dominated by the technology of two companies–Eaton and Varian–whose designs are used in almost 80% of all ion implanters manufactured in the world. Both Eaton and Varian are part of a virtual dynasty created by Dr. Peter Rose in the seventies. This dynasty successfully dominated the world's ion implanter technology from the north shore of the Boston area for almost two decades. However, joint manufacturing ventures in Japan have caused an erosion of this local two-company dominance. Huge expenditures by Asian semiconductor producers have boosted the market share of Japan's suppliers at the expense of American suppliers. In 1989, riding the wave of Japanese leadership in the semiconductor industry, Japan-based suppliers exceeded the growth rate of their United States-based counterparts for the first time.

Two key sources of this growth came in the form of joint ventures with Varian and Eaton. Tokyo Electron Ltd. entered the market in the early eighties in a joint venture with Varian (the joint operation was called TVL). Sumitomo started a similar joint venture with Eaton in the mid-eighties, calling it Sumitomo Eaton Nova (SEN). Overall, Japan now accounts for 37% of the world's ion implanter manufacturing.

4.5.2.1 General Market Overview

The ion implantation equipment market is well over $450M in size. The percentage share for each of the three segments of the market is:

Low-to-Medium-Current	24%
High-Current	70%
High Energy	6%
Ion Implantation†	100%

Fourteen companies compete in this segment of the industry. Five are North American, seven are Japanese, and two are European. The North American companies are Applied Materials, Eaton, Genus (formerly General Ionex), National Electrostatics, and Varian. Japan-based suppliers are SEN, Hitachi, Nissin Electric Co. Ltd., Shinko Seiki, TEL/Varian Ltd., and Ulvac. The two European companies in the market are Balzers AG and High Voltage Engineering Europa. Table 4.5.2.1-1 shows the total number of ion implanters shipped in 1989 by most of these manufacturers.

Including joint ventures, Varian and Eaton have total market shares of 40% and 31%, respectively, with the high-current market their primary battlefield. Competition between the two leaders caused marginal profitability for both and served as a significant barrier to the entry of newcomers.

Ion implanters have often been heavily discounted in order to maintain customer bases. Discounts as high as 50% have been commonplace, making customers hesitant to buy from new vendors. Among the casual-

---

† For more detailed data, please refer to the following areas: Section 4.5.9 gives up-to-date historical sizes for each segment as well as competitive market shares. Projections on the ion implant market are located in Section 1.9.5 of Volume I.

TABLE 4.5.2.1-1

1989 ION IMPLANT EQUIPMENT MARKET

(number of units)

Company	1989 Total	Medium Current	High Current	High Energy
Applied Materials	21		21	
Balzers AG	3	3		
Eaton	77	30	45	2
Genus	8			8
Hitachi	12	7	5	
National Electrostatics	0			0
Nissin Electric Co. LTD	32	20	9	3
Shimadzu				
Shinko Seiki	2		2	
Sumitomo/Eaton	23		23	
Tokyo Electron Ltd.	50	14	36	
Ulvac	6	5	1	
Varian (Including ASM Ion Implant)	92	44	48	0
Other	2	2	0	0
TOTAL	328	125	190	13

Source: VLSI RESEARCH INC

2244-242P

ties: Ion Beam Technologies, which shipped just one medium-current ion implanter before it filed for bankruptcy; and Veeco Instruments, which left the market in 1987, the same year Genus acquired General Ionex. A more recent example is ASM Ion Implant, which shipped its first ASM-220 medium current system in 1987. ASM's system was regarded as innovative–it was the first to employ parallel scanning technology and it eliminated shadowing and channeling, vital to meeting submicron requirements. But with fewer than half a dozen units sold by late 1988, ASM decided to sell the business. The buyer was Varian's Extrion Group, which, for $16M plus royalties, further strengthened the Varian hand. The former ASM-220 system, now called the Extrion-220, is doing well.

4.5.2.1.1 *Low-to-Medium-Current Equipment*

The low-to-medium-current market is the second largest ion implantation segment, accounting for 25% of total sales in 1989. Its portion of the total market has declined in recent years, and is expected to continue to decline. Major reasons include the extending of the current range of high-current implanters downward and an increased demand for high-current implanters due to increased steps in CMOS processing.

There continues to be a market for medium current implanters, however, because of their lower price. Prices are lower because these implanters can function as single wafer systems without the costly mechanical design of batch handling mechanisms as required in high-current designs. The current range of a medium-current implanter allows the processing of one wafer at a time without overheating and device damage. Medium-current implanters are classified as having a maximum beam current of three milliamperes. Equipment types and model numbers offered by these suppliers are shown in Table 4.5.2.3-1 in Section 4.5.2.3.

Table 4.5.9.1-1 in Section 4.5.9 shows the historical market size of low-to-medium-current systems. Five-year sales figures for those companies engaged in the low-to-medium-current ion implanter equipment market are shown in Table 4.5.9.3-1.

4.5.2.1.2 High-Current Equipment

The market for high-current ion implanters made a strong comeback in 1988 and 1989 as the semiconductor world shifted to CMOS. There were only about three to four implants per wafer with NMOS. In contrast, CMOS has as many as 15 implants, and most are high-current. Demand was strong in all parts of the world, with Japan and Korea showing a particularly voracious appetite for high-current machines as virtually all DRAM manufacturers shifted to CMOS. Budgets were revised to accommodate prices, and backlogs stretched into 1990. Typical orders were for four or more units.

Five-year sales among competitors in the high-current implanter market are given in Table 4.5.9.3-2. Since 1979, eight companies have entered the market, but the top two—Eaton (including SEN) and Varian (including TEL)—have been clearly in control, sharing over 90% of the market in 1985. By 1989 their combined share had declined to 76%, but the only serious challenge to date has come from Applied Materials, which is gaining momentum but at this writing remains a distant third.

We pointed out earlier how throughput brings pressure to increase beam current. Equipment beam current can be increased—but only up to a point. When beam current exceeds about two to three milliamperes, new limitations are reached, and a new type of equipment is needed. Current ranges become critical when they reach the very high ranges. For example, high-beam-currents must be space-charge-neutralized with electrons in order to prevent the ion beam from ballooning out of control. This is because of the repulsing nature of the densely packed ion beam. Consequently, the beam cannot be electrostatically deflected while still being held together. Instead, it must be mechanically scanned. This is much more cumbersome and costly than conventional electrostatic scanning. Moreover, such heavy beam currents can cause sputtering to occur. Stainless steel electrodes will not only sputter away under ion bombardment, they'll also release unwanted metals into the wafer. Carbide electrodes, more expensive and difficult to work with, must therefore be used in place of stainless steel. If that isn't enough, batch process must be used in order to keep wafers from overheating. This requires a more complex handling system than the serial handling system used with medium-current machines.

It all adds up to higher equipment costs. For example, prices of high-current systems are still about twice that of medium-current systems, making it hard for semiconductor manufacturers to make the switch. Abbreviated drawings of several types of high-current equipment are shown in Figure 4.5.-2.1-2 through 4.5.2.1-6.

Model numbers and typical selling prices are shown in Table 4.5.2.3-2.

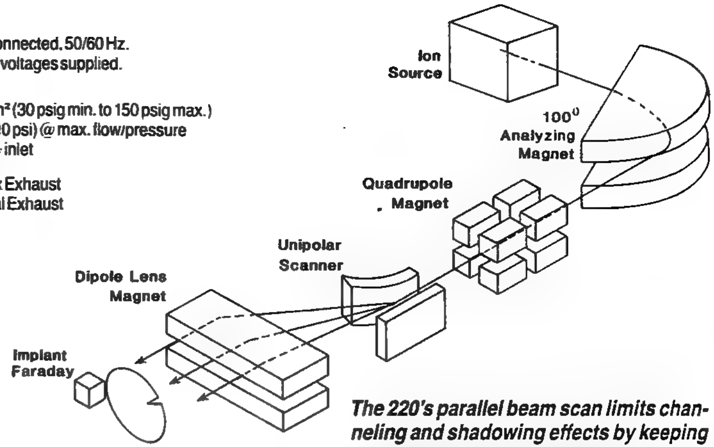
4.5.2.1.3 High Energy Equipment

The high energy implanter market has attracted eight competitors: Eaton, Genus, and National Electrostatics in the United States; Nissin Electric, Shimadzu, and Ulvac in Asia; and High Voltage Engineering Europa, and VG Semiconductor in Europe. Similar to the other ion implant markets, this market has seen a number of casualties. Balzers engaged in the market until 1977. Veeco entered the market briefly in 1981, and finally exited all ion implant in 1987. Varian builds to order.

Machine Specifications

Electrical Power:	28kVa, 480V, 3 phase, 4 wire, Y-connected, 50/60 Hz. Input line transforms for other line voltages supplied.
Cooling Water:	Flow: 0.5 1/sec. (10 gpm) Pressure: 2.1 kg/cm² to 10.5 kg/cm² (30 psig min. to 150 psig max.) Differential Pressure: 0.7 kg/cm (10 psi) @ max. flow/pressure Temperature: 26°C (80°F) max. @ inlet
Ventilation:	2-141 1/sec. (300 cfm) for Gas Box Exhaust 1-282 1/sec. (600 cfm) for Terminal Exhaust
Size:	465 cm × 310 cm × 244 cm high 183" × 122" × 96" high
Weight:	Estimated 6136 kg (13,300 lbs.)

Product specifications subject to change without notice.


Ion Source
100⁰ Analyzing Magnet
Quadrupole Magnet
Unipolar Scanner
Dipole Lens Magnet
Implant Faraday

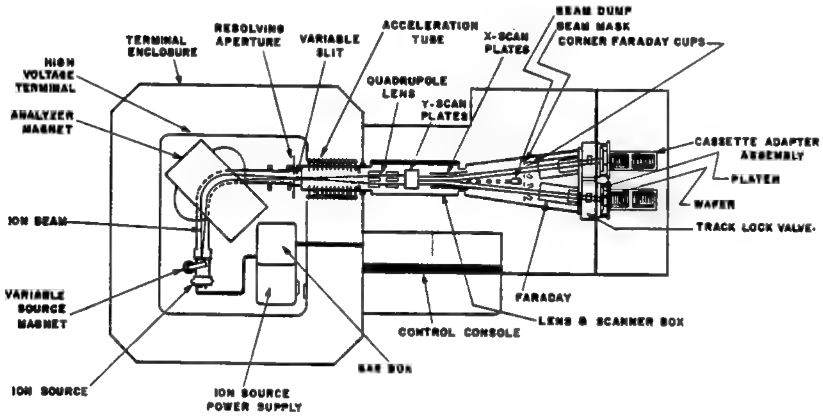
The 220's parallel beam scan limits channeling and shadowing effects by keeping the incident angle of the ion beam constant across the entire wafer surface.

Figure 4.5.2.1-2

Ref: Varian
2244-245

The Extrion-220 Medium-Current Ion Implanter

350D Systems Diagram


TERMINAL ENCLOSURE
RESOLVING APERTURE
VARIABLE SLIT
ACCELERATION TUBE
X-SCAN PLATES
BEAM DUMP
BEAM MASK
CORNER FARADAY CUPS
HIGH VOLTAGE TERMINAL
ANALYZER MAGNET
QUADRUPOLE LENS
Y-SCAN PLATES
CASSETTE ADAPTER ASSEMBLY
PLATEN
WAFER
TRACK LOCK VALVE
ION BEAM
VARIABLE SOURCE MAGNET
FARADAY
LENS & SCANNER BOX
CONTROL CONSOLE
GAS BOX
ION SOURCE
ION SOURCE POWER SUPPLY

Performance Specifications

Energy Range: 10 to 200 keV
Factory tested to 210 keV for stable operation.

Maximum Total Beam Current: 3000μA

Scanned Beam Current on Target:
Minimum — 30 nanoamps
Maximum — (in μA, through a circular mask for 125 mm wafers)

	$^{11}B^{+}$	$^{31}P^{+}$	$^{75}As^{-}$
120-200 keV	600	1500	1500
90-119 keV	500	1250	1250
70- 89 keV	500	1000	1000
50- 69 keV	400	750	750
35- 49 keV	300	350	350

For Doubly Charged Ions:*

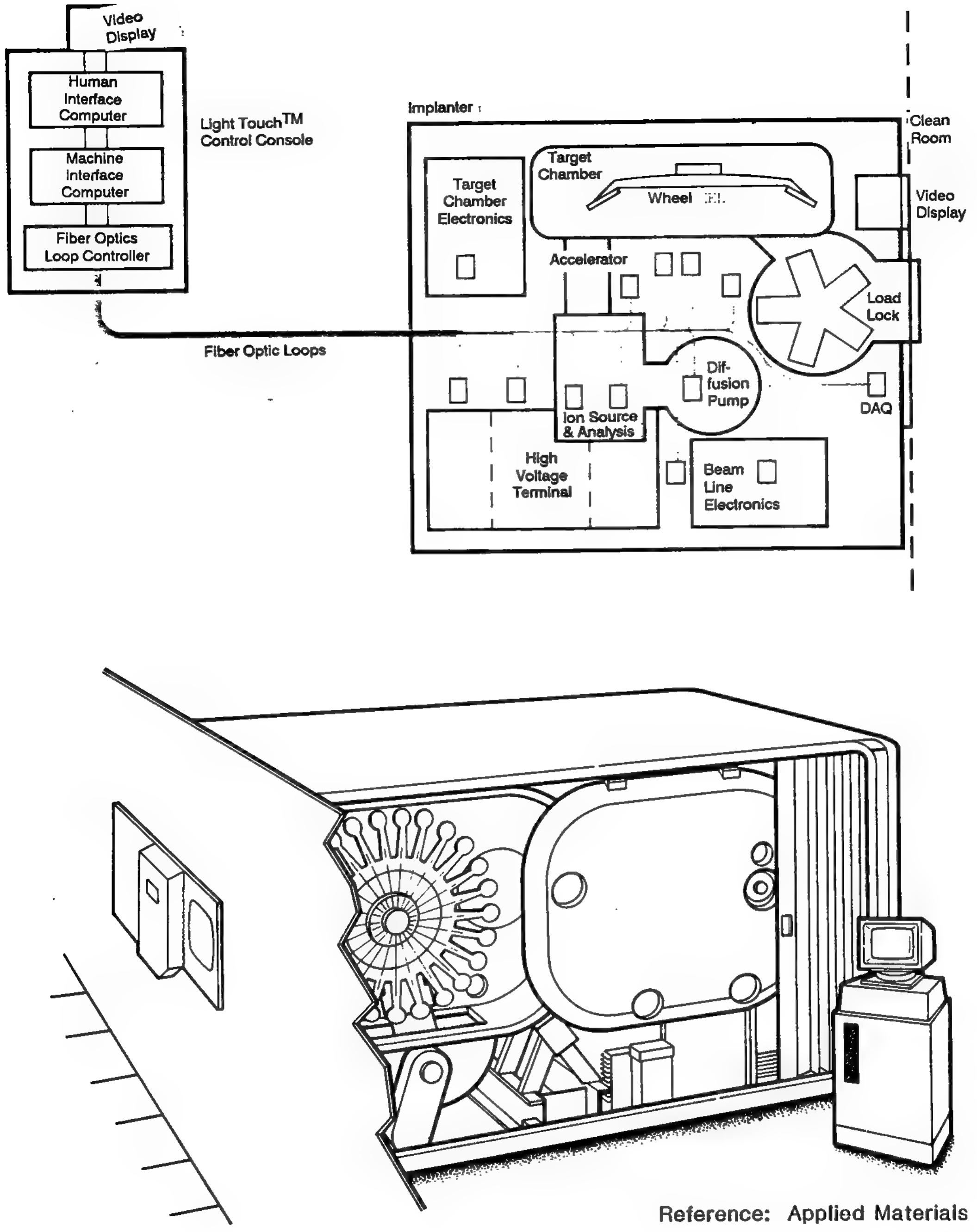
	B^{++}	P^{--}	As^{--}
200-400 keV	5	50	50

Wafer Throughput:†	Up to 350 wafers/hour
Dose Uniformity:	$\sigma \leqslant 0.75\%$ for 2" through 150 mm diameter wafers.
Dose Repeatability:	$\sigma \leqslant 0.5\%$ wafer to wafer and day to day.
Ion Mass Range:	Up to 150 AMU (4.03 MeV AMU Analyzer)
Ion Mass Resolution:	$\frac{M}{\Delta M} \geqslant 100$ where M is the full width at half height.

Figure 4.5.2.1-3

Ref: Varian
2244-246

Varian's Model 350D Medium-Current System

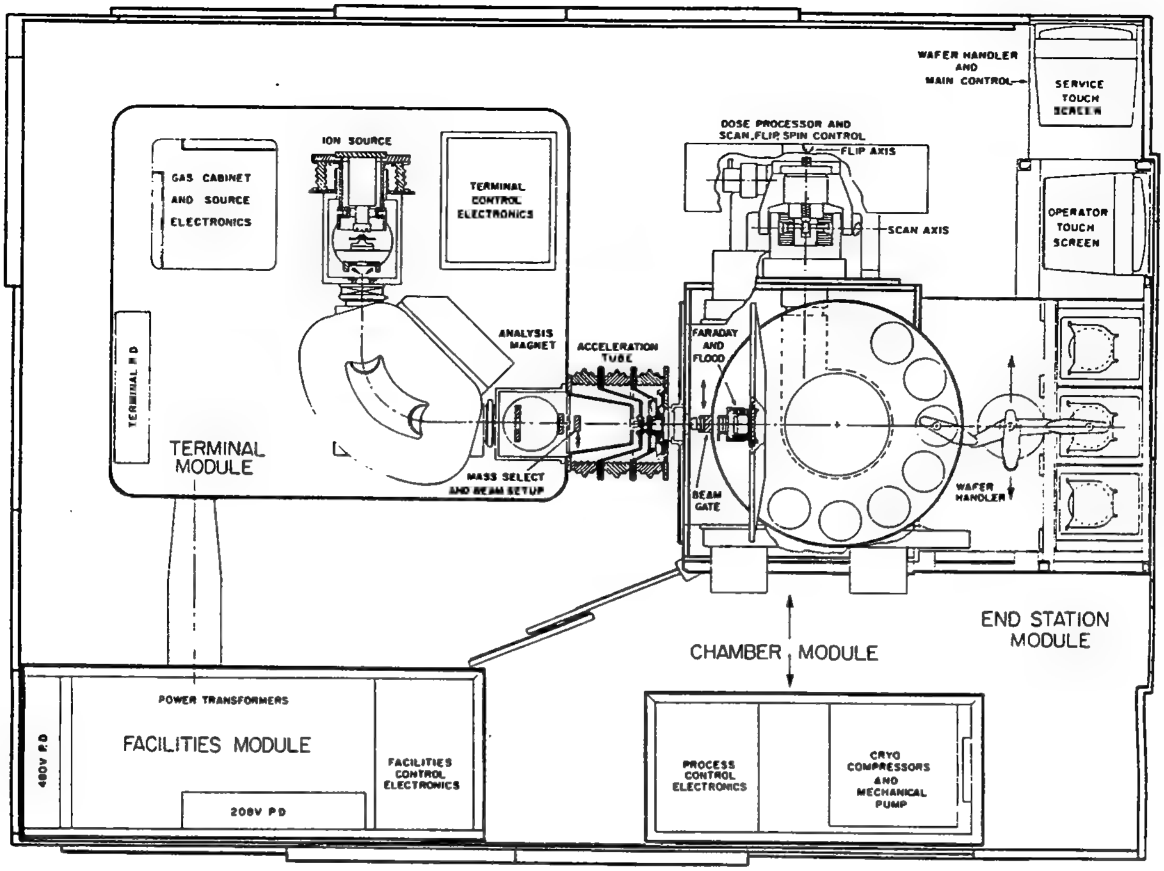

Video Display
Human Interface Computer
Machine Interface Computer
Fiber Optics Loop Controller
Light Touch™ Control Console
Fiber Optic Loops
Implanter
Clean Room
Target Chamber Electronics
Target Chamber
Wheel
Video Display
Accelerator
Load Lock
Dif-fusion Pump
DAQ
Ion Source & Analysis
High Voltage Terminal
Beam Line Electronics

Reference: Applied Materials

2244-247

Figure 4.5.2.1-4

Applied Materials' Percision 9000 High-Current System


WAFER HANDLER AND MAIN CONTROL
SERVICE TOUCH SCREEN
DOSE PROCESSOR AND SCAN, FLIP, SPIN CONTROL
FLIP AXIS
SCAN AXIS
OPERATOR TOUCH SCREEN
ION SOURCE
GAS CABINET AND SOURCE ELECTRONICS
TERMINAL CONTROL ELECTRONICS
TERMINAL P.D
ANALYSIS MAGNET
ACCELERATION TUBE
FARADAY AND FLOOD
BEAM GATE
WAFER HANDLER
TERMINAL MODULE
MASS SELECT AND BEAM SETUP
END STATION MODULE
CHAMBER MODULE
POWER TRANSFORMERS
FACILITIES MODULE
480V P.D
208V PD
FACILITIES CONTROL ELECTRONICS
PROCESS CONTROL ELECTRONICS
CRYO COMPRESSORS AND MECHANICAL PUMP

Extrion 1000 Specifications

PROCESS COMPATIBILITY	
Energy Range	2 - 200 keV
Species	B, P, As, Sb, Ar, Si, O, N
Mass Resolution	> 90 FWHM
Dose Uniformity	0.5% std. dev.
Dose Reproducibility	0.5% std. dev.
Wafer Charging	< 100 Angstrom oxide structures
Wafer Cooling	< 100 C @ 6 kW
Particles Added	<0.10/cm^2 @ 0.3 micron
Flat Orientation (twist)	± 1°
Implant Angle (tilt)	0-10° adjustable
Dose Range	1E11-1E18

WAFER HANDLING	
Wafer Size	3" to 200 mm
Cassettes	Semi standard, plastic
Loading	human or robot interface
Handling	slot -to-slot integrity
Throughput (150 mm)	100 w/hr @ 1E16 200 w/hr @ 1E15

AUTOMATION

- Recipe-Driven Auto Setup, System Monitoring
- SECS Compatible Link, Auto Service Diagnostics
- Computer Guided Service, Friendly Human I/F

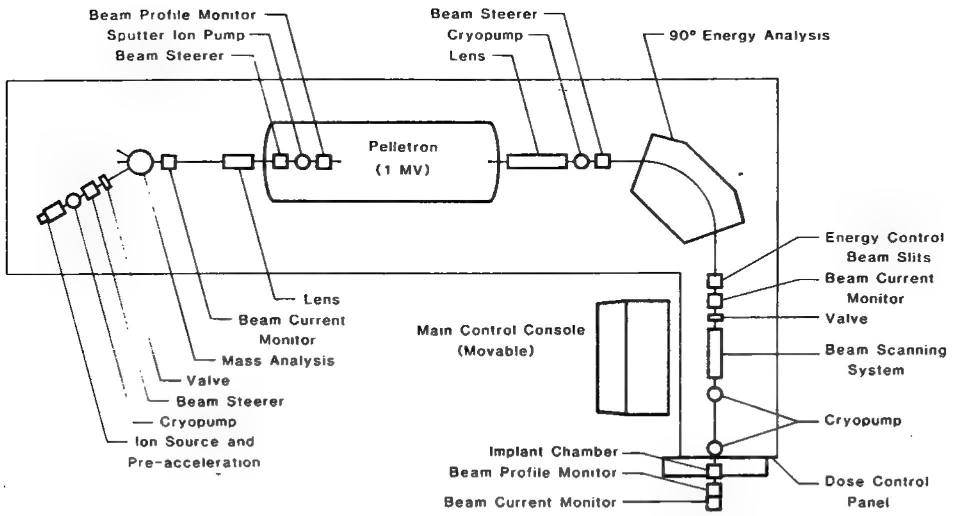
RELIABILITY

•MTBF > 250 hrs	•MTTR < 2 hrs
•MTBA > 24 hrs	•MTTA < 10 minutes
•PM < 5% uptime	•Wafer Breaks < 1/50,000
•Source Life 168 hrs	•Beam Purity ≥ 99.0%

Ref: Varian
2244-248

Figure 4.5.2.1-5

Varian's Extrion-1000 High-Current Ion Implant System


Beam Profile Monitor
Sputter Ion Pump
Beam Steerer
Beam Steerer
Cryopump
Lens
90° Energy Analysis
Pelletron
(1 MV)
Energy Control
Beam Slits
Beam Current
Monitor
Valve
Beam Scanning
System
Cryopump
Dose Control
Panel
Main Control Console
(Movable)
Implant Chamber
Beam Profile Monitor
Beam Current Monitor
Lens
Beam Current
Monitor
Mass Analysis
Valve
Beam Steerer
Cryopump
Ion Source and
Pre-acceleration

Specifications

Beam Energy
From less than 800 keV to more than 3 MeV

Energy Setting Accuracy	1.5%
Repeatability	0.5%

Beam Current
6.0 particle μA of B^{++} at 3 MeV
2.5 particle μA of B^{+} at 750 KeV
(Beam currents for many ion species exceed those for boron. Specifications for other ion species available on request.)

Wafer Throughput
60 wafers/hour; for does of 1×10^{13} ions/cm^2 in 100 mm wafers

Dose Specifications

Accuracy	5% absolute
Repeatability	2%
Uniformity	2%

Shadow (if any) at wafer edge is less than 1 mm.

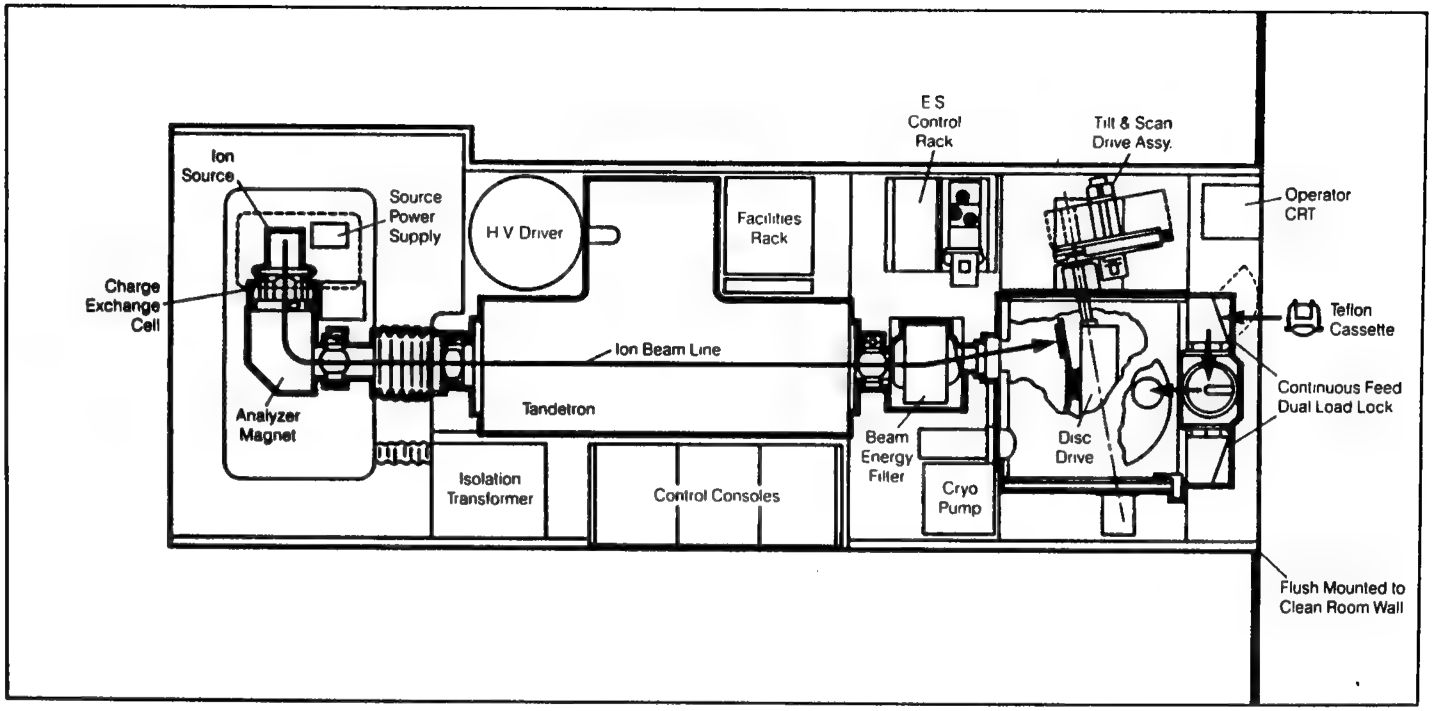
Reference: National Electrostatics Corp.

2244-249

Figure 4.5.2.1-6

The MV-T30 High Energy Ion Implanter by National Electrostatics Corp.

Figures 4.5.2.1-6 and 4.5.2.1-7 show typical high energy ion implanters. Table 4.5.2.3-3 gives model numbers and prices of equipment. The market for high energy systems deteriorated in the early eighties but is now enjoying a comeback as new applications emerge and the need for greater depth of penetration is recognized. Semiconductor manufacturers are just beginning to move these systems into production settings.


Ion Source
Source Power Supply
H V Driver
Charge Exchange Cell
Analyzer Magnet
Ion Beam Line
Tandetron
Isolation Transformer
Control Consoles
Facilities Rack
E S Control Rack
Tilt & Scan Drive Assy.
Operator CRT
Teflon Cassette
Continuous Feed Dual Load Lock
Beam Energy Filter
Cryo Pump
Disc Drive
Flush Mounted to Clean Room Wall

Ref: Genus
2244-250

Figure 4.5.2.1-7

The IX-1500 High Energy Ion Implanter by Genus

Section 4.5.2.2 & 4.5.2.3 have been deleted.

4.5.2.4 *Ion Implant Payback and Economic Models*

Ion implant systems are an essential technology in semiconductor manufacturing. As the number of doping applications requiring ion implantation continues to increase, vendors are put under enormous pressure to further reduce contamination and doping inaccuracies.

Demand for ion implanters and the consequent economics depends on several key items:

a) doping density
b) doping type
c) threshold voltage adjustments
d) energy and current ranges
e) dose time
f) quantity of implants

Each of these has an effect on wafer throughput and, ultimately, the economics of payback. Doping density is perhaps one of the more fundamental determinants. Overall doping densities for any given product type will usually range from a low of about 1E11 atoms per square centimeter to a high of about 1E16. The former requires only a few nanoamperes of ion beam current. The latter may require tens of milliamperes, or more. Actual applications vary significantly, depending on the process.

Bipolar processes make use of between one and eleven implants per wafer, averaging about five implants per wafer. Implant applications differ slightly according to whether the device to be built is a digital bipolar IC, a linear IC or a discrete device. In general, these applications are:

BIPOLAR PROCESS
(1988 Survey Data)

Application	*Doping Density (ions/cm^2) Range*	*Typical Implant*	*Typical #of implants per wafer*
Collector buried layer implants	1E13-1E16	1E15	1
Deep base implants	1E12-1E16	1E15	1
Shallow base implants	1E13-1E16	1E14	1
Resistor implants	1E12-1E16	1E15	1
Emitter implants	1E15	1E15	1
Backside gettering	1E14-1E16	1E15	1

Source: VLSI RESEARCH INC
2244-T1

Ion implanters are universally used by MOS manufacturers for threshold voltage adjustment. This generally consists of one or two implants per wafer. The doping density is relatively light, generally about 1E11 and 1E13 ions/cm^2. Field stops are normally done at about 1E11 ions/cm^2. While most MOS manufacturers perform punch-through implants, only 60% use implanted field stop and field implants. Implantation of MOS resistors is usually done at about 1E12 ions/cm^2. Source-drain implants require much heavier doses. Originally, the doses were between 1E14 and 1E16 with the typical implant dosage of 1E15. Threshold voltage adjust requires the most stringent implant dosage. This is because the threshold voltage to be achieved is a function of the overall surface impurity density, and must be tightly controlled. To achieve this, impurity atoms of the opposite charge are implanted to offset those already present. This results in the subtraction of two very equal doping density quantities. As a result, accuracy requirements become very high—of the order of ten parts in one million or more. Because this is difficult to achieve, several implants are usually required. Normally two, and sometimes three are needed to home-in on the doping value. The number of voltage adjust implants have declined over the years as the accuracy of doping density measurement has improved. The typical threshold adjust is 1E10. These implants must usually be done at very low implant currents, however, and can result in non-uniformity of implants—as will be explained.

Typical dose ranges for MOS implant processes are given below:

MOS PROCESSES
(1988 Survey Data)

Applications	*Doping Density (ions/cm^2) Range*	*Typical Implant*	*Typical # of implants per wafer*
LDD (Lightly Dope Drain)	1E12-1E13	1E13	1.8
Punch-Through	1E11-1E15	1E13	2.3
Wells	1E12-1E13	1E13	2.0
Resistors	1E10-1E13	1E12	1.3
Threshold Adjust	1E09-1E13	1E10	1.5
Fields & Field Stops	1E11-1E15	1E11	1.6
Source Drain	1E14-1E16	1E15	2.1
Enhancements	1E11-1E12	1E11	

Source: VLSI RESEARCH INC
2244-T2

Dopant type comes into play as an economic factor. This is due to the relative inefficiency in achieving adequate species densities. For example, it is difficult to obtain a high density of ionized arsenic atoms. Consequently, the ion beam current for arsenic is low, the time required for doping increases, throughput goes down and the economics of the entire process suffers. Nevertheless, arsenic is a desirable species because of its heavier mass. It stops quickly and does not penetrate deeply into the substrate, thus allowing charge profiles to be more easily obtained. Boron, in contrast, is a very light atom and penetrates so deeply that an uncontrollable 'tail' of unwanted atoms appears in the doping density profile.

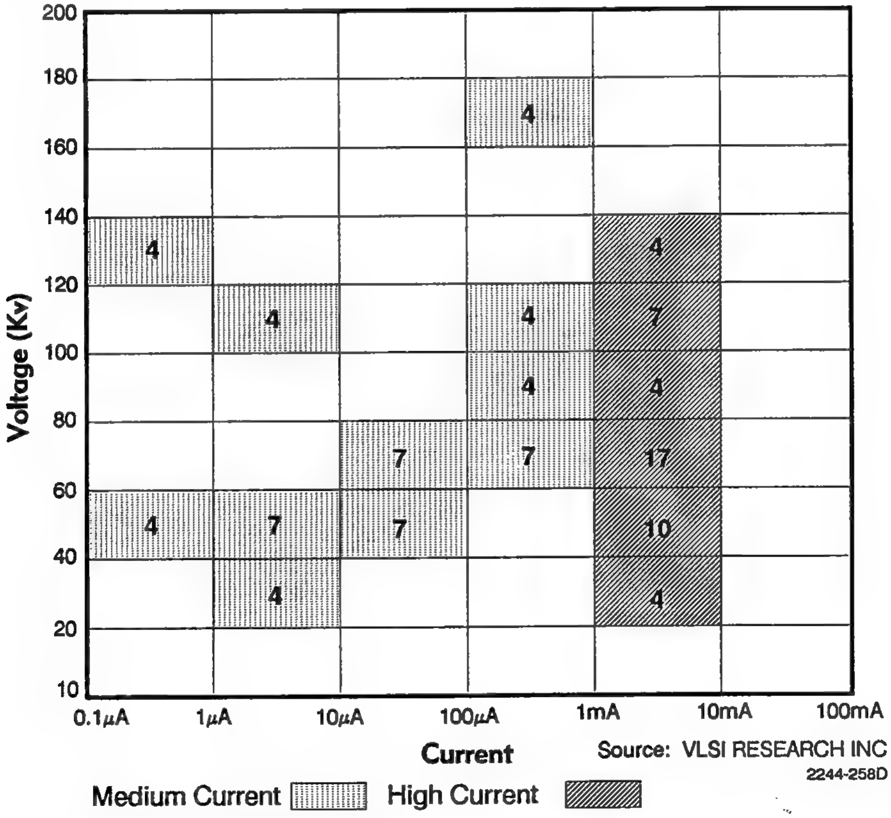
BF^+_2 is being used more frequently, driven by the demand for double-well CMOS. It is becoming more popular because it is heavier than B and results in less channeling. Similarly, higher-current ion implants are possible with BF^+_2 because ion sources can produce more BF^+_2 than B^+. However, one disadvantage that users have found with BF^+_2 is that often 'B' disassociates from BF^+_2 and causes dose inaccuracies.

Current applications of ion implanters is shown in Figure 4.5.2.4-1. There have been marked changes in applications over the past five years, most notably in the voltage range, which has narrowed quite appreciably and has become much more focused on lower ranges. Moreover, medium-current applications have fallen from 75% of the total in 1984 to 56% of the total in 1988. High-current applications almost doubled, from 25% to 44%, during the same period, with most new applications in the lower voltage ranges.

It's clear that ion implanters will be used in larger numbers of applications. CMOS is the driving force behind the increased number of mask layers, which of course call for more implants. Figure 4.5.2.4-2 shows a sample of CMOS well structures. Each will require significant numbers of ion implant steps to achieve the current profiles. Table 4.5.2.4-3 shows some of the applications for ion implantation.

More applications—a number of which are shown in Figure 4.5.2.4-4—are requiring high energy ion implanters. There has, for example, been renewed interest in the direct formation of buried layer collectors via very high voltage accelerators. These require machines with one to two megavolt accelerating potentials.

High energy systems can also be used to reduce the thermal budget needed for processing. Such applications are principally being driven by new HCMOS devices. CMOS wafers require 16 to 30 hours in a diffusion furnace. Deep implantation could reduce much of this. Additionally, CMOS well depths require deep penetration. Four hundred keV to one MeV high energy

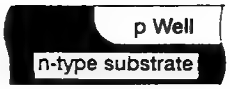
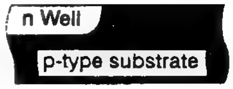
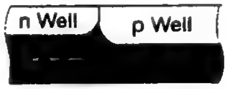
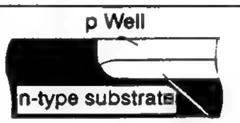
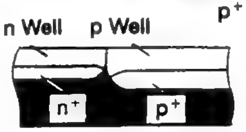
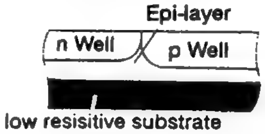
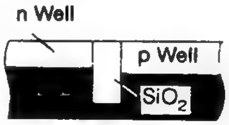


Source: VLSI RESEARCH INC
2244-258D

*1% of applications are above 200 keV.

Figure 4.5.2.4-1

Typical Ion Implanter Beam Current Usage
(distribution in percent)

Item		*Schematic Cross-Section*
Well structure of device fabrication	Single Well	 p Well n-type substrate  n Well p-type substrate
	Dual Well	 n Well p Well
Well structure for Latch-up immunity	Retrograde Well	 p Well n-type substrate p⁺  n Well p Well n⁺ p⁺
	Epitaxial substrate	 Epi-layer n Well p Well low resisitive substrate
	Trench isolation	 n Well p Well SiO₂

Source: Semiconductor World 1987.4

2244-259

Figure 4.5.2.4-2

CMOS Well Structures

TABLE 4.5.2.4-3

ION IMPLANT APPLICATIONS

MOS	***Bipolar***
LDD	Collector Buried Layer
Punchthrough	Deep Base
Wells	Shallow Base
Resistors	Resistor
Threshold Adjust	Emitter
Source/Drain Gettering	
Field/Field Stops	
Gettering	
Isolation	
ROM Programming	

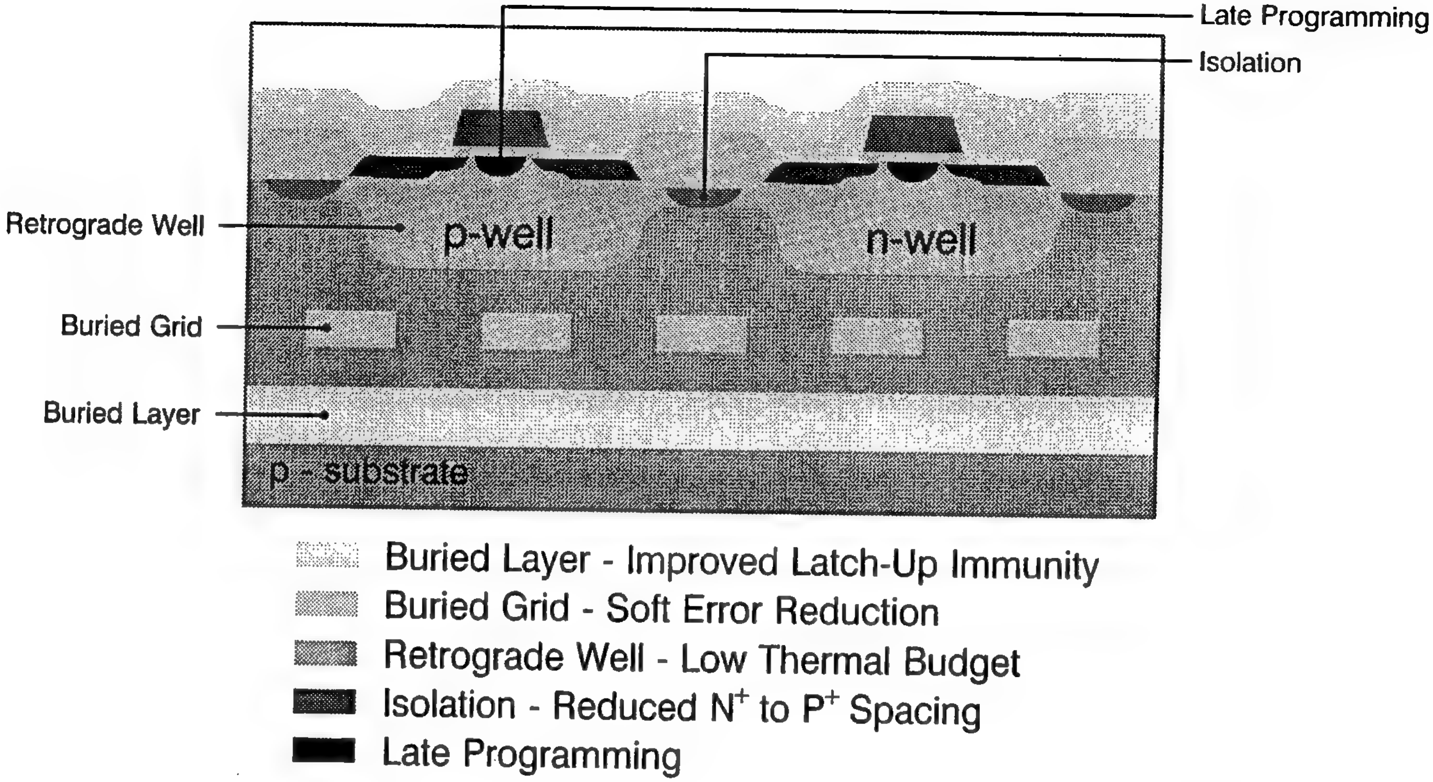
Source: VLSI RESEARCH INC
2244-260W

systems are required to achieve these depths. Proponents of ion implanters claim retrograde well implants have a significant impact on thermal budgets.

A buried high energy implant may be a cost effective alternative to epitaxial deposition in avoiding latch-up. Epitaxy adds approximately $10 to the cost of in-house processed epi wafers. Epi wafers on the open market cost upwards of $50 for a six-inch wafer. A buried-layer high energy ion implant consists of placing a narrow p+ layer under the n-well to isolate the well from the substrate. It follows field oxidation and the n-well drive-in. One advantage to buried layer implants is that the p to p+ transition is sharper than in the cast of p on p+ epi material. This could help to eliminate latch-up more effectively than epitaxial wafers. Precise doping densities and precise ion implant placement are requirements for today's devices in the submicron range. As the need for more precise doping continues, and device structures become more complex, ion implant will become even more critical. Issues that continue to plague ion implant users are scanning error and particulate control. Forty percent of ion implant users list these among their most pressing concerns, and it's clear that both issues need to be addressed promptly in order to meet submicron requirements.

Implantation in trenches makes precision and angle of incidence more critical. Figure 4.5.2.4-5 demonstrates what is probably one of the most complex assignments for ion implantation—a 16-Mbit surrounded capacitor cell (SCC). It starts with a tilt-angle implant of arsenic and boron into the side walls of a shallow trench (a); then a deep trench is etched (b); followed by a resist-masked tilt-angle implant of boron and arsenic into its side walls (c); finally, the trench bottom is profiled via an etch and a vertical boron implant (d). Complex procedures like this illustrate why new generations of ion implanters will be required to implant on the side walls of trenches.

The angle of incidence of ions over the wafer surface is principally determined by the type of ion implanter being used. If the angle of incidence is not consistent across the wafer, doping inconsistencies arise. In order to address this issue in more detail, it is important to differentiate between the two types of ion implanters. Serial implanters scan ion beams side to side, electrostatically across the wafer. The angle of incidence in this type of system is typically five degrees for a six-inch wafer. Batch systems employ a rotating disc, with several wafers clamped to the disc. They are mounted on an angle to use the centrifugal force created with the rotating disc. In batch systems the angle of incidence is typically seven degrees. The Varian medium-current system, a hybrid serial implanter, reduces the angle of incidence. The implanter beam is scanned electrostatically in the horizontal direction. A parallel scanned beam at the wafer is gained by a non-uniform field dipole magnet. Claimed capability is less than 0.35°. Similarly, Applied Materials offers on option on its high-current batch ion implanter that allows the user to vary the angle of incidence from zero to seven degrees.


Late Programming
Isolation
Retrograde Well
Buried Grid
Buried Layer
p-well
n-well
p - substrate
▨ Buried Layer - Improved Latch-Up Immunity
▨ Buried Grid - Soft Error Reduction
▨ Retrograde Well - Low Thermal Budget
▨ Isolation - Reduced N^+ to P^+ Spacing
■ Late Programming

Ref: Genus
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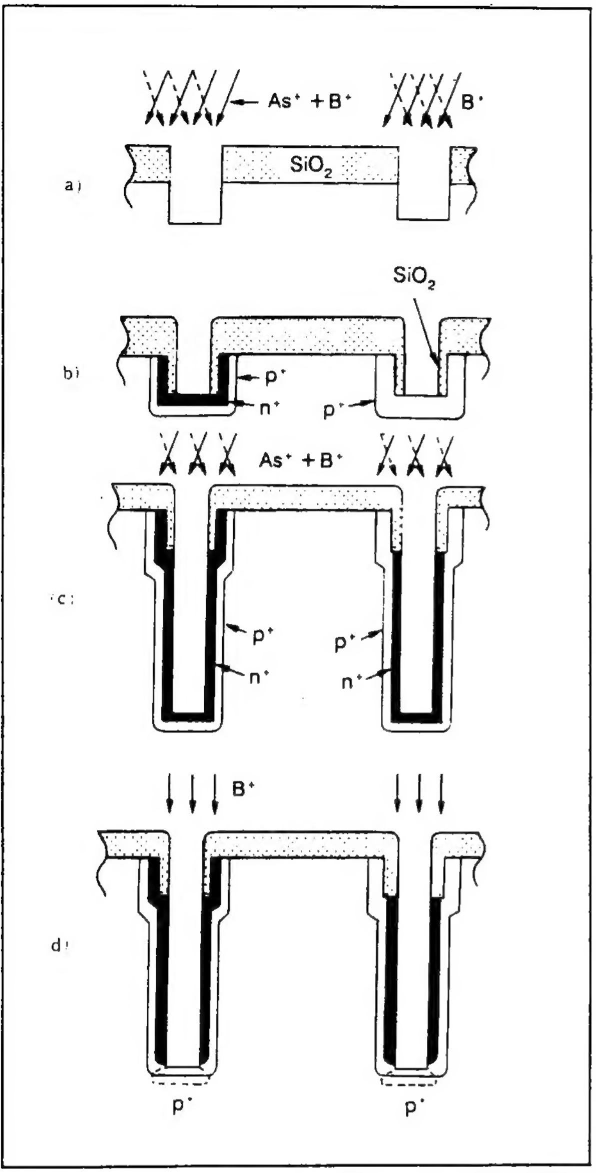
Figure 4.5.2.4-4

MeV IMPLANT APPLICATIONS



Source: Semiconductor World 1988.4

2244-262

Figure 4.5.2.4-5

SCC Cell Ion Implantation

Deep trenches are being employed more frequently to increase the packing density in today's VLSI devices. Many 4-Mbit DRAMs use this method for isolation or as vertical storage capacitors. Trench isolation frequently requires an implant into the bottom of the trench, and the deeper the trench, the more difficult the task. Trenches can have an aspect ratio of 10, making implantation limited to the bottom of the trench very difficult. One of the difficulties encountered with trench isolation is the incidence of a parasitic channeling in the side walls of the trenches. This causes a leakage current which may shift the device threshold causing device malfunctions. Implantation of boron into the sidewalls has been found to suppress this occurrence. In order to produce this type of implant, the angle of incidence must be maintained to ±0.5% over the wafer surface.

Shadowing is another problem that occurs with an improper angle of incidence. Shadowing happens when the wafer is tilted in respect to the ion beam and the masking material is thicker than the feature size of the implantation area. The degree of shadowing depends on implant angle, but whatever the degree it can negatively influence device performance. This is particularly true with LDDs, which are used to reduce the channel's electric field near the drain and prevent electromigration. Two LDD processes are shown in Figure 4.5.2.4-6. The decreased electrical field helps to prevent device failure caused by the introduction of 'hot' electrons into the gate dielectric.

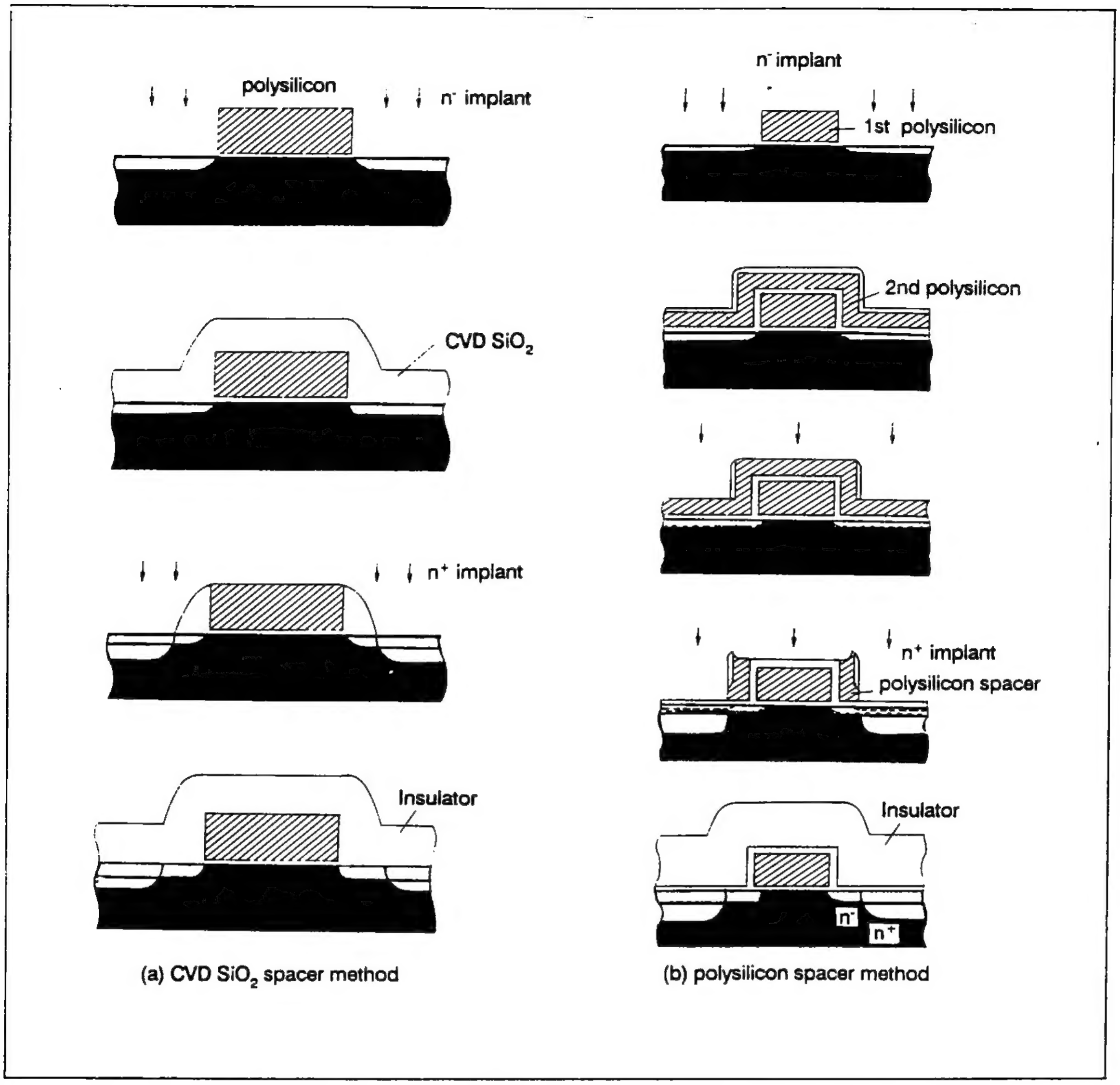
Particulate problems continue to abound. Sixty percent of ion implant users cite particulates from end-stations as the primary problem with ion implanters. One of the most frustrating problems for owners is wafer breakage. It not only results in the total loss of yield for each broken wafer, but can cause yield losses to wafers processed later. Even broken edges or minor nicks that occur during handling can result in a total loss during subsequent processing.

End-station design is the most challenging factor in preventing these losses. It must process the wafer in a vacuum, transfer the wafer from atmosphere to vacuum, and then bring it back to atmosphere without damaging or contaminating its surface. Most systems rely on gravity feed and sliding wafers on surfaces within the implanter. Other systems include both gravity feed and edge handling devices that grip the edge of the wafer in two or more places. Either method can subject wafers to damage.

Similarly, wafers become contaminated by particles generated during contact with the handling mechanism. There are many stages of handling where a wafer is at risk of being crushed or broken. In gravity feed systems, the wafer must follow guides and be deaccelerated in a controlled fashion. It must not contact or bounce off structures within the unit prior to coming to a stop. Wafers can be crushed when load-locked in and out of vacuum, unless they are correctly positioned in the load-lock valve area.

Mispositioning can occur due to ineffective transmission sensors or when wafers rebound from the cushioning stops during a gravity-feed operation. Damaged wafers or broken pieces can block whole wafers from assuming the correct position in a load-lock and cause the wafers to remain on the valve seat when the valves close. This type of accident is common and results in serious particle contamination and significant downtime.

Another source of wafer breakage is improper service and alignment of end-station components. When components are removed for service, or when wafer size changes require elements of the end-station to be exchanged, improper placement or replacement or improper adjustment of various set screws and leveling devices can cause serious problems. Often a marginal adjustment of the mechanical settings and stops will shift out of tolerance after a few hours of operation and subsequent wafer damage will result.


polysilicon
n⁻ implant
CVD SiO₂
n⁺ implant
Insulator
(a) CVD SiO₂ spacer method
n⁻ implant
1st polysilicon
2nd polysilicon
n⁺ implant
polysilicon spacer
Insulator
n⁻
n⁺
(b) polysilicon spacer method

Source: Semiconductor World 1987.4

2244-263

Figure 4.5.2.4-6

LDD Fabrication

Notes